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**Josep Franklin Sihite**

**2013**

# **Failure Analysis of Power Transformer Based on Fault Tree Analysis**

Dissertation

Submitted in partial fulfillment of the requirements for the degree of Doctor of  
Philosophy of Kyoto University

by

**Josep Franklin Sihite**



**Kyoto University**

**May 2013**

## Abstracts

A modern electric power system is a very large and complex network consisting of generators, power transformers, transmission lines, distribution lines, and other devices. Power transformer is one of the most important electricity equipment in power system. It plays important roles both in transmission and in distribution system by transferring the electricity energy.

Power transformers condition should be maintained because of its importance to electricity network. There is an increasing need for better diagnostic and monitoring tools to assess the condition of transformers. Many monitoring testing and condition assessment techniques have been used by utilities.

In this thesis, we propose a new approach in order to assess power transformer condition by using fault tree analysis. The reliability assessment of power transformer assessment resulted qualitative and quantitative fault tree analysis. The qualitative analysis of the fault tree results minimal cut sets and qualitative importance. First step in fault tree analysis is developing and constructing the model of fault tree of power transformer system base on real system of switchyard GI Simangkuk system in Indonesia. The causes are deductively identified as the event causing every possible hazard by constructing a fault tree. The fault tree is constructed in a hierarchical structure with a single top event. The qualitative results help in focusing attention on main apparatus of power transformer that contributed to the unreliability of the system. Through qualitative fault tree analysis of power transformer can be found that the strongest and the weakest point are tank sub-system and winding sub-system, respectively.

Quantitative analysis is performed to estimate the probability of the top event occurrence and sub top event occurrences or unreliability of the power system. To perform quantitative analysis, first, a failure rate every basic components must be obtained and entered in the calculation properties for each lowest-level event. Secondly, before quantitative fault tree calculation is performed, we have to determine whether the fault tree is static or dynamic gate. Static gates will be solved by conventional fault tree while dynamic gates of tree will be by transformed into equivalent Markov models. Not only the

probability of occurrences of the top event (power transformer failure), but also every gates can be obtained by quantitative methods.

The quantitative fault tree analysis resulted the rankings of quantitative contribution of sub-systems to the occurrence of top event are obtained as winding sub-system, OLTC sub-system, bushing sub-system, core sub-system, and tank sub-system, respectively. The consistency of this result with the general weakness of the power transformer.

Importance measures analysis presents the rank of the component importance measures quantitatively according to their contribution to system reliability. For this task the Birnbaum importance measures, critically importance measures, and Fussel-Vessely importance measures are employed. These methods present the rank of the component importance measures quantitatively according to their contribution to system reliability and safety. This result shows that only 14 basic event give 89 % contribution to the power transformer system reliability. These methods also resulted the winding sub-system contains the higher ranking of importance basic events in power transformer system.

Finally as conclusion of this thesis presents the fault tree method is a simple method and easy to apply for the power transformer system and recommend to utilities as an alternative method in order to contribute for resolving the reliability problem assessment of power transformer to ensure the safety operation and distribution of GI Simangkuk switchyard in Sumatera Electricity Interconnection, Indonesia.

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## Symbols and Abbreviations

AC	<i>Alternating Current</i>
ANSI	American National Standards Institutes
BDDs	Binary Decision Diagrams
BIM	Birnbaum Importance Measure
CCF	Common Cause Failure
CIGRE	<i>Conseil international des grands réseaux électriques</i> (The International Council on Large Electric Systems)
CIM	Criticality Importance Measure
EPRI	Electric Power Research Institute
FTA	Fault Tree Analysis
FT	Fault Tree
FVIM	Fussell-Vesely Importance Measure
FO-FA	Forced Oil -Forced Air
GI	<i>Gardu Induk</i> (Switchyard)
GDP	Gross Domestic Product
GSU	Generator Step-Up
GW	Giga Watt
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission

IEEE	Institute of Electrical and Electronics Engineers
kV	Kilo Volt
kVA	Kilo Volt Ampere
MCS	Minimal Cut Set
MW	Mega Watt
OLTC	On-Load-Tap-Changer
PLC	Programmable Logic Controller
PLN	<i>Perusahaan Listrik Negara</i> (the state-owned electricity utility)
PT	Power Transformer
SAS	Substation Automation System
TE	Top Event
TWh	Terrawatt hour

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# Chapter 1

## Introduction

### 1.1 Background

Indonesia's economy has emerged from the global financial crisis in a strong position having achieved a GDP growth rate 4.5 % in 2009 and with growth for 2010 projected to be 5.6 % . Indonesia grew at 6.63 % in 2007 and 6.0 % in 2008.

This robust growth is spurred by a population of 235 million which undergoing an unprecedented degree of urbanization and industrialization. This growth should see Indonesia's demand for electricity increase at 7 % to 9 % per year for the foreseeable future. This should translate into growth in electricity demand from an estimated 135 TWh in 2010 to 167 TWh by 2014 [4, 49, 50].

Business Monitor International is now forecasting Indonesian real GDP growth averaging 5.72% per annum between 2010 and 2014, with a 2010 assumption of 5.20%. Population is expected to expand from 240 million to over 250 million over the period, with GDP per capita and electricity consumption per capita forecast to increase by 63% and 18% respectively. The country's power consumption is expected to increase from an estimated 135 TWh in 2010 to 167 TWh by the end of the forecast period, theoretically meaning a slight theoretical surplus in generation, assuming 5.0% annual average growth in electricity generation during 2010-2014 [49,50].

According to the Indonesia National Electricity Sector Master plan 2006-2026, between 2010 and 2019, is forecasting an increase in Indonesian electricity generation of 55.3%, which is above average for the Asia Pacific region. This equates to 28.4% in the 2014-2019 period, up from 21.0% in 2010-2014. PED growth is set to rise from 15.8% in 2010-2014 to 25.5%, representing 45.3% for the entire forecast period. An increase of 23% in hydro-power use during 2010-2019 is a major element of generation growth. Thermal power generation is forecast to rise by 58% between 2010 and 2019 [4, 49, 50,52].

The growth of electricity needs of Java-Bali System in the period 2009-2018 increased from 107,8 TWh in 2009 to 250,9 TWh in 2018 or an average growth of 9,5%. For outside of Java-Bali system over the same period increased from 30,9 TWh to 74,3 TWh, or growth an average 10,3% per year [3]. Therefore, PLN has a master plan to develop new power plan about 40,952 GW for Java-Bali System and 16,5 GW of outside Java-Bali System [4].

The power utility business in Indonesia is conducted only by the state-owned electricity utility, PLN (*Perusahaan Listrik Negara*)[1], which currently operates as a monopoly in the market, generation, transmission, distribution and supply. In power generation sector, 80% of power is generated by PLN and the rest is fulfilled by the IPPs (Independent Power Producers). About 75% and 12% of power is consumed in Java-Bali and Sumatra respectively [2]. The supply of electricity is therefore emerging as a potential constraint on Indonesia's long-term growth and development ambitions. With growth in power demand of 7 % - 11 % per year the situation is also likely to only more critical [51].

The expansion of the electricity supply in Indonesia has been considered to fulfill the increasing of electricity demand, especially in Sumatra. This area is the biggest consumer of electricity outside of Java-Bali system and growth rapidly. Therefore PLN has a master plan to develop a new power plant and its infrastructure [5]. Asahan I hydro electric power plant is a new power supply for Sumatra interconnection. This plant produces 2 x 90 MW electricity. Simangkuk Switchyard is built by PLN to connect Asahan I with Sumatra interconnection system. This site has been operating since January 2011. Simangkuk is operated by computer system control (substation automation system, SAS) and equipped with 4 power transformers 275 kV [3]. Protection systems of Simangkuk switchyard equipped with software and computer system. This equipment is digital high voltage protection equipment by PC and can be used as main protection and backup protection for 220 kV and higher voltage grade power transmission lines. This software also protects transformers from any abnormal conditions [6].

A modern electric power system is a very large and complex network consisting of generators, transformers, transmission lines, distribution lines, and other devices. A well-

designed power system provides high-quality electric energy to the user instantly, constantly, and exactly in the amount that is needed. It would be, however, impractical or uneconomic to design and build a fault-proof power system. Thus power systems and their components need appropriate protection from natural hazards and equipments failures, as well as human error.

The objectives of every electric power utility are to maintain network integrity and stability throughout, and to promote higher reliability of power supply to customers without interruption. Power transformers condition should be maintained because of its importance to electricity network. There is an increasing need for better diagnostic and monitoring tools to assess the condition of transformers [7].

Transformer failure is able to have a significant economic impact due to long lead times in procurement, manufacturing, and installation in addition to high equipment cost. According to the Electric Power Research Institute (EPRI), extending the useful life of power transformer is the single most important strategy for increasing life of power transmission and distribution infrastructures, starting with generator step-up transformers at the power plant itself [8,9].

As transformers age, their internal condition degrades, which increases the risk of failure. Failures usually triggered by severe conditions, such as lightning strikes, switching transients, short circuits, or other incidents. When the transformer is new, it has sufficient electrical and mechanical strength to withstand unusual system conditions. As transformers age, their insulation strength can degrade to the point that they cannot withstand system events such as short circuit faults or transient over voltages.

To prevent these failures and to maintain transformers in good operating condition is a very important issue for utilities. Traditionally, routine preventive maintenance programs combined with regular testing were used. With deregulation, it has become increasingly necessary to reduce maintenance cost and equipment inventories. This has led to reductions in routine maintenance. There is an increasing need for better diagnostic and monitoring tools to assess the reliability and condition of power transformer.



Many testing, monitoring testing and condition assessment techniques have been used by utilities. This thesis presents fault tree method to assess the reliability of power transformer as a simple method and easy to apply for the power transformer system.

## **1.2 Objective**

The main objective of this thesis is to analyze reliability of power transformer system by fault tree analysis. This thesis demonstrates the application of fault tree analysis method to power transformer assessment of switchyard GI Simangkuk, Sumatera power interconnection system in Indonesia. The reliability assessment of power transformer assessment resulted qualitative and quantitative fault tree analysis.

The qualitative analysis of the fault tree results minimal cut sets and qualitative importance. The qualitative results help in focusing attention on main apparatus of power transformer that contributed to the unreliability of the system.

Quantitative analysis is performed to estimate the probability of the top event occurrence and sub top event occurrences or unreliability of the power system. The quantitative fault tree analysis resulted the rankings of quantitative contribution of sub-systems to the occurrence of top event.

Importance measures analysis presents the rank of the component importance measures quantitatively according to their contribution to system reliability. For this task the Birnbaum importance measures, critically importance measures, and Fussel-Vessely importance measures are employed.

## **1.3 Goal and Contribution of the Dissertation**

Monitoring and diagnostic methods of power transformer have been developed since the invention of this equipment in power system. There are a variety of tools available to evaluate the condition of power transformer, yet there is an increasing need for better diagnostic and monitoring tools to assess the condition of transformers.

In this dissertation, we propose a new approach in order to assess power transformer condition by using fault tree analysis. We have aimed to develop the fault tree analysis of power transformer system by using both static fault tree and dynamic fault tree

Our motivation to conduct the research can be considered as an attempt to provide a practical approach to resolve of power transformer assessment in power system of developing country such as Indonesia. This method has been used and refined over the ensuing years, is attractive because it does not require extensive theoretical work and it is a practical tool that any engineer can learn to use easily. This analysis will document the cause and effect relationship between failures at various subsystem levels, to identify the most important failures and weakness points in the systems.

Finally conclusion and recommendation are proposed in order to contribute for resolving the reliability problem assessment of a practical power transformer to ensure the safety operation and distribution of GI Simangkuk switchyard in Sumatera Electricity Interconnection, Indonesia.

## **1.4 Definitions**

### **1.4.1 Standard for Probabilistic Risk Assessment**

The following definitions are provided to ensure a uniform understanding of select terms as they are specifically used in this thesis based on Standard for Probabilistic Risk Assessment for Nuclear Power Plant Application [62] .

1. *Basic event* : an event in a fault tree model that requires no further development, because the appropriate limit of resolution has been reached.
2. *Component* : a basic event in a power transformer fault tree model.
3. *Common cause failure* : multiple component faults that occur at the same time or that occur in a relatively small time window and that are due to a common cause.
4. *Dependency* : requirement external to an item and upon which its function depends and is associated with dependent events that are determined by, influenced by, or correlated to other events or occurrences.
5. *Diagnosis* : examination and evaluation of data to determine either the condition of an structure, systems, components or the cause of the condition.

6. *Event tree* : a logic diagram that begins with an initiating event or condition and progresses through a series of branches that represent expected system or operator performance that either succeeds or fails and arrives at either a successful or failed end state.
7. *Failure* : an unacceptable deviation from the design tolerance or in the anticipated delivered service, an incorrect output, the incapacity to perform the desired function
8. *Fault* : a defect, imperfection, mistake or flaw of varying severity that occurs within some hardware or software component or system. “Fault” is a general term and can range from a minor defect to a failure.
9. *Fault realization or error* : the manifestation of a fault in a system or the information that is processed by the system or a manifestation in the internal system state.
10. *Failure probability* : the likelihood that an structures, systems, and components fail to operate upon demand or fail to operate for a specific mission time.
11. *Failure rate* : expected number of failures per unit time, evaluated, for example, by the ratio of the number of failures in a population of components to the total time observed for that population
12. *Fault tree* : a deductive logic diagram that depicts how a particular undesired event can occur as a logical combination of other undesired events.
13. *Minimal cut set* : a smallest combination of basic events whose occurrence results in the occurrence of the top event of a fault tree.
14. *Permanent fault* : a fault with lasting effects. The failed component or system must be replaced.
15. *Safety system* : those systems that are designed to prevent or mitigate a design basis accident.
16. *“State of component” fault* : a fault of a component due to either the failure of the component or the failure of a command to the component.
17. *“State of system” fault*: a fault with a system-level effect and which is not necessarily localized at a given component.

18. *System* : is a deterministic entity comprising an interacting collection of discrete elements.
19. *System failure* : termination of the ability of a system to perform any one of its critical design functions.
20. *Top event* : the initial event of a fault tree or success tree. Also called the undesired event in the case of a fault tree.
21. *Transient fault* : a fault of limited duration that causes no permanent hardware damage. Transient faults can be caused by excessive heat, power disruptions, timing issues or environmental influences, for example. It is often possible to recover from a transient fault without discarding the affected component or system.
22. *Unavailability* : the fraction of time that a system or component is no capable of supporting its function including, but not limited to, the time it is disabled for test or maintenance.
23. *Unreliability* : the probability that a system or component will not perform its specified function under given conditions upon demand or for a prescribed time.
24. *Undesired event* : the top event of the fault tree.

#### **1.4.2 Standard for power transformer system.**

For the purpose of this thesis, the following definitions shall apply [63]

1. *Auto-transformer* : a transformer in which at least two windings have a common part.
2. *Core* : The ferrous center part of a transformer or inductor used to increase the strength of the magnetic field. It carries the flux and forms the magnetic coupling between primary and secondary.
3. *Power transformer* : a static piece of apparatus with two or more windings which, by electromagnetic induction transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose transmitting electrical power.

4. *Oil-immersed type transformer* : a transformer of which the magnetic circuit and windings are immersed in oil .
5. *On-load tap-changer* : a device for changing the tapping connections of a winding, suitable for operation while the transformer is energized or on load.
6. *Winding* : the assembly of turns forming an electrical circuit associated with one of the voltages assigned to the transformer.

## 1.5 Structure of the Dissertation

The dissertation is organized as follows.

**In chapter 2**, we describes the need of assessment and maintenance of power transformers due to outages effect of failures, high cost of maintenance and replacement, increase of world demand, aging effect and used of old transformer, and computer protection system failure. In this chapter we present power transformer design and construction as well the power transformer failures and problems. We also describes the monitoring and diagnostic methods of transformers assessment which have been developing in recently years.

**In chapter 3**, shows the process of developing and constructing the model of fault tree of power transformer system based on switchyard GI Simangkuk system in Indonesia. The causes were deductively identified as the event causing every possible hazard by constructing a fault tree. The fault tree was constructed in a hierarchical structure with a single top event. Furthermore in this chapter we conduct the qualitative fault tree analysis of power transformer.. Fault tree analysis (FTA) of the power transformer was performed to investigate the causes for the fault in power transformer operation. Qualitative analysis on the FT yielded minimal cut sets and qualitative importance. By qualitative analysis of the FTA, we found the weakness of power transformer system.

**In chapter 4**, we present quantitative FTA in assessing the reliability of power transformer for a switchyard. First step is to determine whether the fault tree is static or dynamic. To generated calculated results, the static entities are computed using standard combinatorial

techniques. The dynamic entities are transformed into equivalent Markov models. The results for these various entities are then brought together using techniques employed for “generalized fault tree analysis” to produce calculations. This result will help the decision maker to improve the reliability of power transformer system.

**In chapter 5**, we conduct importance measures analysis of power transformer system components. In this research we present an application and results of the importance measures analysis of a power transformer system of GI Simangkuk switchyard in Indonesia by using Birnbaum importance measures, critically importance measures, and Fussel-Vessely importance measures. These methods present the rank of the component importance measures quantitatively according to their contribution to system reliability and safety.

**In chapter 6**, we present a brief summary of the research carried out in this thesis and proposes some potential future research topics.

## Chapter 2

### Power Transformers Assessment

#### 2.1 Introduction

A modern electric power system is a very large and complex network consists of generators, transformers, transmission lines, distribution lines, and other devices. The purpose of the electric power system is to produce, supply, transmit and use electric power. This power system is also known as the grid and can be broadly divided into the generators that supply the power, mostly electricity generation comes from coal, natural gas, biomass, nuclear fission, wind, solar, and hydropower. The transmission system that carries the power from the generating centre to the load centre, and the distribution system that feeds the power to nearby homes and industries, such system as those shown in Figure 2.1.

A well-designed power system provides high-quality electric energy to the user instantly, constantly, and exactly in the amount that is needed. It would be, however, impractical or uneconomic to design and build a fault-proof power system. Thus power systems and their components need appropriate or reasonable protection against natural hazards and equipments failures, as well as human errors. The objectives of every electric power utility are to maintain network integrity and stability throughout, and to promote higher reliability of power supply to customers without interruption [1].

Power transformers are required throughout modern interconnected power system. IEEE / ANSI defines a transformer as a static electrical device, involving no continuously moving parts, used in electric power systems to transfer electric energy in any part of the circuits between the generator and the distribution primary circuits through the use of electromagnetic [2].

The transformer installed at power stations or substation must be operate fault free over a long period of time. Transformers in turn rely on a number factors to provide desired

voltage and current. The primary function of the power transformer is to reduce the transmission cost in electrical power system. It reduces the transmission losses by reducing the required current for transmission. This cost reduction is achieved by increasing the transmission voltage in the system. For long transmission routes, very high voltages up to 750 kV are preferred while for common transmission 550 and 400 kV are preferred. To fulfill the variety of voltages and power, power transformers are required from generation plant to customers. The voltage adjustment are done by step up or step down transformers. Step up transformer increases the voltage ratio on secondary side while step down transformer decreases the voltage ratio on the secondary winding side of transformer.

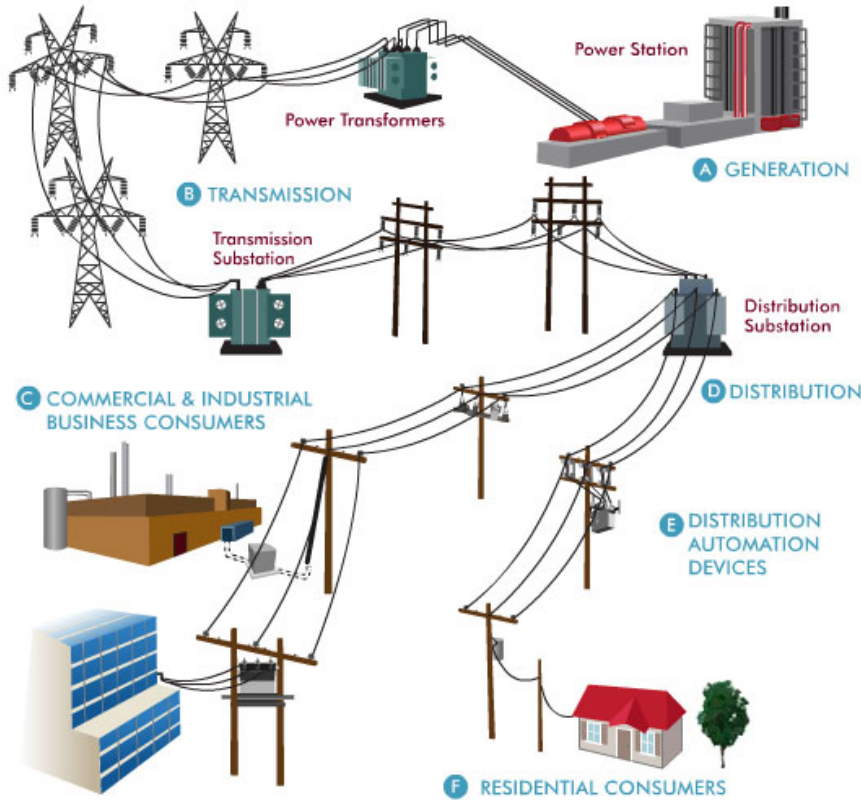


Figure 2.1 Power generation and distribution system.

Source : <http://www.bravoprojects.co.in/transmission.php>



The term power transformer is used to refer to those transformer is used between the generator and the distribution circuits, and these are usually rated at 500 kVA and above. Power systems typically consist of a large number of generation locations, distributions areas, and interconnections within the system or with nearby systems, such as a neighboring utility. The complexity of the system leads to a variety of transmission and distribution voltages. Power transformers must be used each of these points where there is a transition between voltage levels.

Power transformers are selected based on the application, with the emphasis toward custom design being more apparent the larger the unit. Power transformers are available for step-up operation, primarily used at the generator and referred to as generator step-up (GSU) transformers, and for step-down operation, mainly used to feed distribution circuits. Power transformers are available as single-phase or three-phase apparatus.

Power transformer is one of the most importance electricity equipment in power system. It plays an important role both in transmission and distribution system by transferring the electricity energy, from one voltage level to another, under magnetic induction reaction. When a failure occurred on a transformer, it also means that the electricity could not be delivered to customer. The sizes of the transformers range from as low as few kVA to over a few hundred MVA, with replacement cost range from a few hundred dollars to millions of dollars

Power transformers are usually very reliable, with a 20-40 years design life [8]. In practice life of a transformer can be as long as 60 years with appropriate maintenance. However, the in-services failure of a transformer is potentially dangerous to utility personnel through explosions and fire, potentially damaging to the environment through oil leakage, is costly to repair or replace, and may result in significant loss of revenue.

As transformers age, their internal condition degrades, which increases the risk of failure. Failures are usually triggered by severe conditions, such as lightning strikes, switching transients, short circuits, or other incidents. When the transformer is new, it has sufficient electrical and mechanical strength to withstand unusual system conditions. As

transformer age, their insulation strength can degrade to the point in which they cannot withstand system events such as short circuit faults or transient over voltages [1].

## **2.2 The Importance of Power Transformers Assessment**

Power transformer is one of the most important electricity equipments in power system. It plays an important role both in transmission and distribution system by transferring the electricity energy, from one voltage level to another, under magnetic induction reaction. When a failure occurred on a transformer, it also means that the electricity could not be delivered to customer. The sizes of the transformers range from as low as few kVA to over a few hundred MVA, with replacement cost ranging from a few hundred dollars to millions of dollars. Power transformers are usually very reliable, with a 20-40 design life [8]. The practice life of a transformer can be as long as 60 years with appropriate maintenance. However, the in-services failure of a transformer is potentially dangerous to utility personnel which causes explosions and fire, potentially damaging the environment through oil leakage. Its repair or replace may lead to significant loss of revenue.

As transformers age, their internal condition degrades, which increases the risk of failure. Failures are usually triggered by severe conditions, such as switching transients, short circuits, or other incidents. When the transformer is new, it has sufficient electrical and mechanical strength to withstand unusual system conditions. As transformers age, their insulation strength can degrade to the point in which they cannot withstand abnormal events such as short circuit faults or transient over voltages [1].

Transformer failure may have a significant economic impact due to long lead times in procurement, manufacturing, and installation in addition to high equipment loss. According to the Electric Power Research Institute (EPRI), extending the useful life of power transformer is the single most important strategy for increasing life of power transmission and distribution infrastructures. This strategy starts with generator step-up transformers at the power plant itself [9].

In 1983 CIGRE Working Group 12.05 under the leadership of Bossi [23] published a report summarizing the results of an analysis of data collected on failures of large

transformers not more than 20 years old occurring between 1968 and 1978, relating to more than 1,000 failures in a total population of more than 47,000 unit-years which corresponds to a general failure rate figure, irrespective of the voltage classes and function of the units, of the order of 2 %. Nevertheless, if voltage classes are taken into account, it seems that the failure rate increases with voltage. The data available were also analysed as a function of the failure first component involved and of the presumed cause. The statistically more substantial results are those concerning substation transformers with on-load-tap-changer (OLTC). Regarding the first component involved (Fig 2.2) it may be noted that about 33 % of failures are due to the windings [24].

The necessity of power transformer condition assessment in the field of power systems are as follows :

#### **1. The outages of power system.**

The outage of power transformers can influence power system reliability. It is difficult to directly measure the impact of an outage for the reliability of power grid. But it is possible to estimate it by means of some criteria. For instance, the outage of a generator step-up transformer is often more serious than the outage of a transmission transformer and the outage of a power transformer with high loading is more influential than a low loading [10]. Health and safe operation of power transformers is so important that unexpected fault and shutdown may result in a great accident and get a high penalty in lost output cost, particularly under an ever-increasing competition environment.

#### **2. High cost of maintenance and replacement.**

Power transformers are fundamental parts of power system. When they get damaged or they may fail. Then they must be repaired or even replaced. Power transformers life-span is lengthened in order to avoid high replacement costs. This in turn increases the effort for maintenance and repair. Thus, costs move partially from replacement to maintenance and repair. In order to avoid skyrocketing maintenance and repair costs, capacities of maintenance and repair need to be downsized to a point where a high reliable power transformer can be still guaranteed.

### 3. High growth of electricity demand.

World electricity demand is projected to be doubled between 2000 and 2030 at an annual growth rate of 2.4 % each year. Electricity demand growth has the strongest trend in developing countries, where the demand climbs by over 4 % per year over the projection period, more than tripling by 2030 [11]. Consequently, a new infrastructure of power system, especially power transformer, must be developed. Similarly, more load of power transformers will be required. The growth of loads and the increased bulk power transaction accelerate the power transformers physical ageing process as a result of increasing the operating stresses.

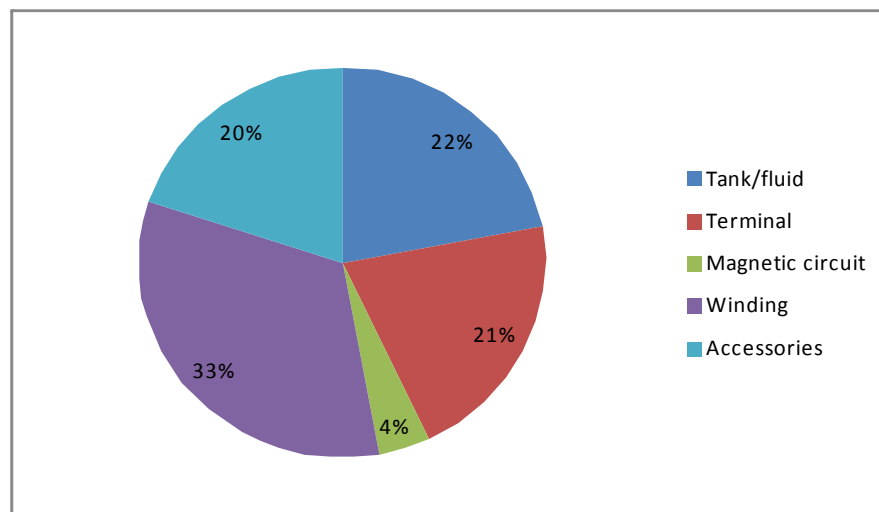


Fig 2.2. Typical failure distribution for power transformers

### 4. The aging effect and utilized of old transformer.

The age distribution of the transformers is reflective of power system equipment around the globe, with a high percentage of transformers older than 20 years, as indicated in figure 2.3 [12]. Apart from this, older transformers also occupy strategic nodes on the network. Effective asset managements are thus crucial in minimizing risks to the distribution network. According to standard organization such as American National Standards Institute(ANSI)/ Institute of Electrical and Electronic Engineers (IEEE), average generator

step-up transformers life average is considered to be 20 to 25 years[13], and in practice life of a transformer can be as long as 60 years with appropriate maintenance. Nowadays, many of electricity utilities are using old transformers (older than 25 years). In Japan, the age of more than half of the existing transformers will be more than 30 years old in the near future. The utilities expect life time of these transformers to be around 40 to 50 years old [14]. The utilities expect life time of transformers to be around 40 to 45 years more than the manufacturers have designed [15]. Using good method of assessment and maintenance, the life of transformer can be extended. It's important to pursue both cost reduction and reliability assurance by rationalization of maintenance methodology and technically/economically optimized refurbishment plan.

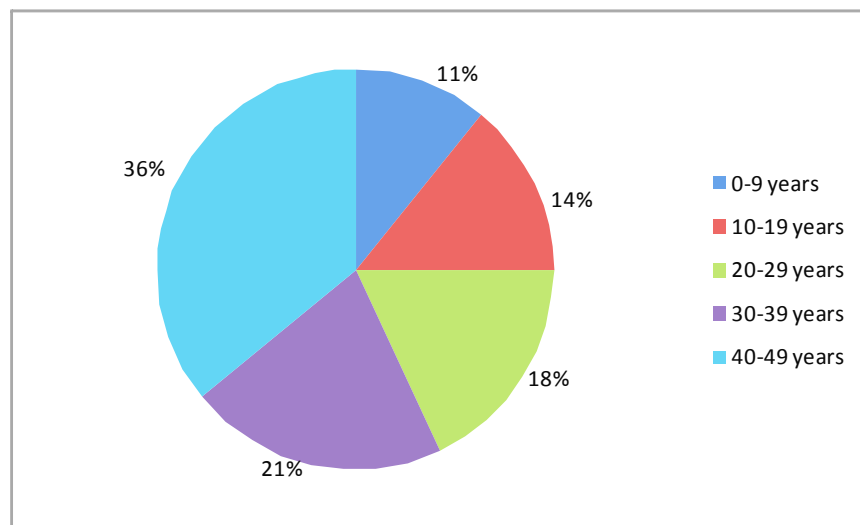


Fig. 2.3 Power transformers age distribution.

## 5. Computer and software errors

Nowadays, power transformer protection system operates based on software system using PLC (Programmable Logic Controller). If any abnormal condition in the power transformer, its protection system will be automatically activated, so that the damage of any equipments be minimized. Since the hardware system reliability increases due to the

advancement of technology, systematic failures such as software design errors become a significant contributor to system accident. Another main causes to system accident is human errors. The reliability of computerized protection system of power transformer need to be evaluate for assurance of system safety [16].

### **2.3 Power Transformers Design and Construction**

Transformer function is based on the principle that electrical energy is transferred efficiently by magnetic induction from one circuit to another. When one winding of a transformer is energized from an alternating current (AC) source, an alternating magnetic field is established in transformer core. Alternating magnetic lines of force, called flux, circulate through the core. With a second winding around the same core a voltage is induced by the alternating flux lines. A circuit, connected to the terminals of the second winding, results in current flow.

The construction of a transformer depends upon the application. Transformers intended for indoor use are primarily of the dry type, they can also be liquid immersed. For outdoor use, transformers are usually liquid immersed. This section focuses on the outdoor, liquid-immersed transformers, which used at switchyard of GI Simangkuk in Indonesia power system, Sumatera interconnection, Type 250 MVA, 275 kV, three windings with cooling system oil immersed, forced oil (FO)-forced air (FA) cooling system equipped with fans, oil pumps and radiators, such as those shown in Figure 2.2.

As electrical devices that transfer energy from one electrical circuit to another by electromagnetic coupling without moving parts, power transformers are normally regarded as high reliable assets. Further, they are designed and constructed by time-proven technology and material. It is generally believed that the power transformer at the turn of the 20<sup>th</sup> century already a mature product and the essential features of the device remain unchanged to date, although the transformer continues to evolve [19,20].

The principles that govern the function of all electrical transformers are the same regardless of size or application [20]. The typical power transformer is submerged in mineral oil for insulation and cooling and is sealed in an airtight metallic tank. Low and high voltage power lines lead to and from the coils through bushings. Inside the transformer

tank, core and coils are packed close together to minimize electrical losses and material costs. The mineral oil coolant circulates by convection through external radiators.

The essential parameters that characterize the ideal transformer depend to a large extent, on the properties of the core. The properties that are critically important in transformer core material are permeability, saturation, resistivity and hysteresis loss. It is generally believed that it is in the core that most significant advances in power transformer design construction have been made [20]. The construction of a power transformer varies throughout the industry. The basic arrangement is essentially the same and has seen little significant change in recent years. The main components of the power transformer are the core, winding, insulation and tank

The performance of power transformer depends on dielectric insulation and cooling system, because these two systems are intimately related, firstly, the amount of heat both the core and winding conductors determines the permanence and durability of the insulation, and the dielectric insulation system itself is designed to carry off some of the heat.

It is vital that the insulation utilized in a power transformer must be able to separate the difference circuits; isolate the winding core and outer case from the circuits; provides mechanical support for the electrical coils and withstand the mechanical forces imposed by conductor insulation, high density pressboard for inter-winding and inter-phase insulation and paper for lead insulation. The critical properties that determine the functional life of dielectric oil/paper insulation are chemical purity, thermal stability, mechanical and dielectric strengths.

## **2.4 Power Transformers Failures**

During the course of its life, the power transformer as a whole has been suffering the impact of thermal, mechanical, chemical, electrical and electromagnetic stresses during normal and transient loading conditions. A failure ultimately occurs when any operating stresses exceeds its strength of the above key properties. In addition, failure process in power transformers are often complex and so cooperation between manufacturers, utilities, academics is necessary to understand then.



Figure 2.4 The power transformer

Source : Sumatera interconnection system, PLN.

A useful way of thinking about failure of a power transformer could be illustrated in Figure 2.5, as proposed by CIGRE Work Group 12.18 [21,22]. Typical transformer functional failure mechanisms are given by the CIGRE Work Group 12.18 [21, 22].

Utilities experiences thus far reveal most power transformer failures are not due to deterioration, but localized damage or ageing due to some defects in design and manufacture, application and maintenance. Sometimes a power transformer does fail without any warning notice. In most cases, however, the symptoms of developing fault and failure can be detected, prevented or eliminated [23].

Nowadays, power transformers are generally very reliable with expected services life of 40 years or more due to the advance of in manufacture and technology. On the other hand the design factor of system and the operation condition are varied, the circumstance and the condition of power transformer for the same type equipment are also different. In such a condition it is very difficult to establish the fault model for all condition of the power transformer system.



The withstand strength of a transformer will naturally decrease over its life according to various aging processes, but may deteriorate faster than normal under the influence of agents of deterioration or if some abnormal destructive process occurs. Theoretically it is possible to distinguish between reversible processes (often referred to as defects) and irreversible ones (faults), although such a distinction is not always clear-cut. Ideally, the presence of defects or faults would be detected by monitoring and diagnostic test [21].

Operational stresses are usually dominated by intermittent events such as lightning strikes or short circuits. As an example of the changing stresses over the life of a transformer, consider the mechanical stress imposed on a winding. When the transformer is new, the windings will be aligned to minimize the stress of electromagnetic forces during short circuits. As the transformer insulation ages, the paper insulation will shrink and may result in a reduction of clamping pressure, thereby reducing mechanical strength.

Because of the random nature of the key operational stresses it is unlikely that it will be possible to predict when the final failure will occur. However, if remnant strength and operational stress could be quantified adequately, it would be possible to determine when the circumstances were such that a failure could occur. A key task in managing transformer services lives would therefore appear to be the quantitative assessment of the relevant remnant withstand strengths of power transformers and operational stresses [24].

## **2.5 Power Transformer Monitoring and Diagnostics Method**

The power transformers are in general classified into categories from the condition point of view : normal, aged and normal, defective, faulty, and failed. When the transformer is normal, no remedial action is justified since there no evidence of degradation. Normal aged transformer can not be totally free defect but it is usually taken acceptable. Defective transformer gradually deteriorates more unless remedial

action is carried out. Faulty transformer may or may not be possible to improve condition by remedial action.

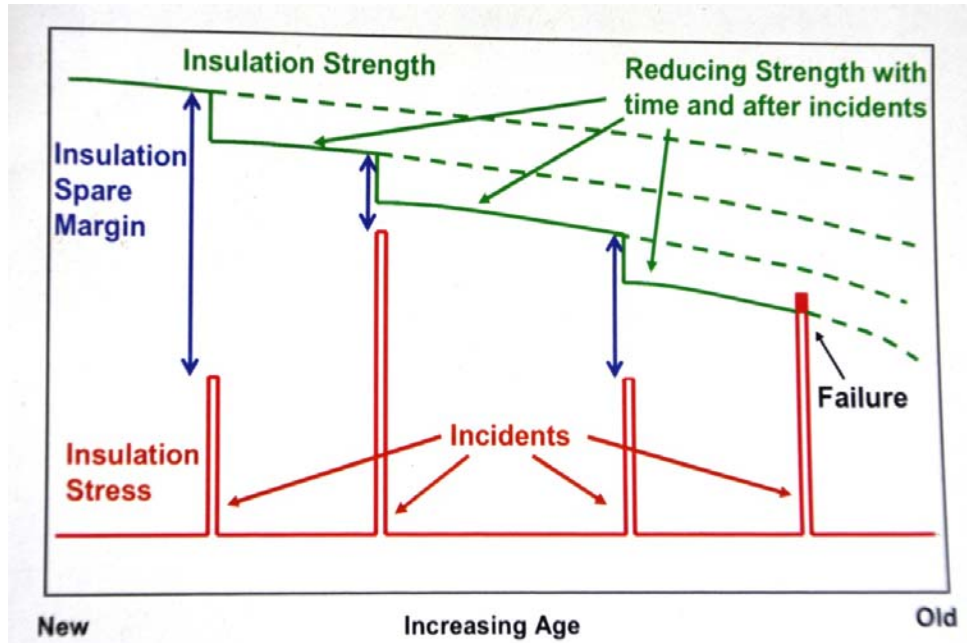


Figure 2.5 A conceptual failure model proposed by CIGRE WG 12.18 [37,38]

Failed transformer can not be kept in service. Remedial action is required before the transformer can be returned to service [18].

Overheat and overpressure are general causes of transformer damage. Therefore a cooling system is necessary to protect it. Power transformers are normally loaded according to their rated power, whereas network transformers are loaded to 100 % or more in emergency only. Therefore, monitoring systems are particular attractive for power transformers and network transformers in the upper voltage levels. Monitoring and diagnostic methods of transformers assessment was developed in recently years. A more comprehensive approach is clearly needed to evaluate the remaining life of transformer as a whole. To asses the overall condition of a transformer reliably, several monitoring techniques are used and under investigations.

Monitoring and diagnostic methods have been develop since the invention of this equipment in power system. The term “monitoring” describe a basic parameter measurement with threshold alarms. The term “diagnostics” indicates the additional of sophisticated analysis, such an expert system capable of providing an assessment of equipment condition and suggested actions

There are a variety of tools available to evaluate the condition of power transformer [26-36]. Common used diagnostic methods are based on : chemical diagnostic methods, electrical diagnostic method, thermal diagnostic method, optical diagnostic method and mechanical diagnostics.

They also can be separated into traditional diagnostic methods that have been seen widespread use for many years and non-traditional methods that range from methods that are starting to be used to methods that are still in the research stage [25]. Traditional diagnostic methods include dissolved gasses analysis, insulating oil quality testing, power factor testing, winding resistance, winding ratio and thermography. Non-traditional transformer monitoring techniques, a great deal of new development have been used for transformers. Non-traditional methods include in service testing method, recovery voltage measurement, winding insulating oil testing, tap changer/motor monitoring, internal temperature measurement, on-line power factor measurement, dielectric spectroscopy, winding movement detection, software diagnostics and experts systems [1].

## **2.6 Proposed Method**

The basic idea of the proposed transformer condition assessment analysis is using fault tree analysis (FTA) to obtain the probability of component failure leading to transformer failure. This method will assesses transformer condition to determine a policy of maintenance and operation. Fault Tree Analysis is a tool with which protection engineers can easily compare the reliability of a proposed protection of transformers. Major motivation of quantifying reliability issues include the best decision-making on how to

improve the system, how to manage dependability and security and how to maintain the transformer safely with the least money.

Fault tree analysis can be applied not only an existing system but also to a system that is being designed. When it is applied to a system being designed of which specific data do not exist, FTA can provide an estimate of the failure probability and the important contributors using generic data to compile the design components or concepts. When applied to an existing system, FTA can be used identify weakness and evaluate possible upgrades. fault tree analysis can also be used to monitor and predict system behavior. Furthermore, fault tree analysis can be used to diagnose causes and take potential corrective measures for an observed system failure [17]. This method has been used and refined over the ensuing years, is attractive because it does not require extensive theoretical work and it is a practical tool that any engineer can learn to use easily. In recently years, computer software programs are available to assist in developing and analyzing complex fault trees.

Assessing the condition of power transformer by using fault tree analysis, the first step is modeling the system and failures sequences with fault tree. Using minimal cut sets method we can make qualitative evaluation of the model. Secondly, we aim at acquiring and generating all information necessary for the quantification of the models such as initiating events data, component failure, repair and maintenance data, human error data, etc. Markov methods are employed to solve the dynamic, dependent sections of the fault tree and binary decision diagram to solve the static fault tree sections. This analysis will documenting the cause and effect relationship between failures at various subsystem levels, identifying the most important failures and weakness points in the systems which help to provide appropriate maintenance to extend life service and increase the reliability of power transformers. To ensure reliability of computer system of power transformer, it can approach by using accident analysis based on system control concepts [16] .

## 2.7 Summary and Conclusion

Power transformers are required throughout modern interconnection power system. This apparatus are also the most expensive and strategic components of any power system. Therefore, it is very important to provide a high quality maintenance and accurate condition assessment to protect it from any damage and maintain transformer life services. When a failure occurs in a power transformer, the whole system will be failed and the electricity could not be delivered to customer. Each utility has to assure their reliability in order to maintain electrical power system stability by assessing transformer condition.

This chapter also describes the need of assessment and maintenance of power transformers such as outages effect of failures, high cost of maintenance and replacement, increase of world demand, aging effect and used of old transformer, and computer protection system failure.

As transformers age, their internal condition degrades, which increases the risk of failure. Failures are usually triggered by severe conditions, such as lightning strikes, switching transients, short circuits, or other incidents. When the transformer is new, it has sufficient electrical and mechanical strength to withstand unusual conditions. As transformers age, their insulation strength can degrade to the point that they cannot withstand system events such as short-circuit faults or transient over voltages.

To prevent these failures and to maintain transformers in good operating conditions is a very important issue for utilities. The ultimate goal of transformer diagnostics and condition assessment is to have a set of devices/systems to monitor and anticipate the transformer failure, so that appropriate action can be taken before forced outage occurs.

Monitoring and diagnostic methods have been developing since the invention of this equipment in power system. There are a variety of tools available to evaluate the condition of power transformer. Common used diagnostic methods are based on : chemical diagnostic methods, electrical diagnostic method, thermal diagnostic method, optical diagnostic method and mechanical diagnostics. They also can be separated into traditional diagnostic methods that have been seen widely spread use for many years and non-traditional methods that range from methods starting to be used to methods that are still in the research stage.

There is an increasing need for better diagnostic and monitoring tools to assess the condition of transformers [80]. In this chapter we propose a new approach in order to assess power transformer condition by using fault tree analysis. In the next chapter, we use the fault tree analysis as one of alternative methods in order to assess and monitoring transformers condition.

## **Chapter 3**

### **Constructing and Qualitative Fault Tree Analysis**

#### **3.1 Introduction**

Power transformer is an electrical device used to convert low voltage to very high voltage electricity intended to upgrade efficiency in power electricity transmission and distribution. Power transformer is one of the main equipments in power systems. When a failure occurs in a power transformer, the whole system will be failed and the electricity could not be delivered to customer. Each utility has to assure their reliability in order to maintain electrical power system stability by assessing transformer condition [37].

There are varieties of tools available to evaluate the conditions of power transformers. They can be separated into traditional diagnostic methods that have been seen widespread by used for many years and non-traditional methods that are starting to be used and that are still in the research stage. Traditional diagnostic methods include dissolved gasses analysis, insulating oil quality testing, power factor testing, winding resistance, winding ratio and thermography. For non-traditional transformer monitoring techniques, a great deal of new development has been used for transformers. Non-traditional methods include in service testing method, recovery voltage measurement, winding insulating oil testing, tap changer/motor monitoring, internal temperature measurement, on-line power factor measurement, dielectric spectroscopy, winding movement detection, software diagnostics and experts systems [1,15].

### **3.2 Fault Tree Analysis Methods.**

The basic idea of the proposed transformer condition assessment analysis is using Fault Tree Analysis (FTA) to obtain the probability of component failure leading to a power transformer failure. A fault tree analysis is a logic diagram that shows potential events affecting system performance and the relationship between potential events.

This method will assess transformer condition to determine a policy of maintenance and operation. Fault Tree Analysis is a tool with which protection engineers can easily compare the reliability of proposed protection of transformers.

FTA can be used to identify the system weakness and evaluate possible upgrades. fault tree analysis can also be used to monitor and predict behavior. Furthermore, fault tree analysis can be used to diagnose causes and give potential corrective measures for an observed system failure [17,38 ]. This method has been used and refined over the ensuing years, is attractive because it does not require extensive theoretical work, and is a practical tool that any engineer can learn to use easily.

The fault tree technique was introduced in 1962 at the bell Telephone Laboratories, in connection with a safety evaluation of the control launching system for the intercontinental minuteman ballistic missile [45]. The Boeing Company improved the technique and introduced computer programs for both qualitative and quantitative fault tree analysis. At the 1965 Safety Symposium, sponsored by the University of Washington and the Boeing Company, several papers were presented that expounded the virtues of fault tree analysis [46]. The presentation of these papers marked the beginning of the wide-spread interest in using fault tree analysis as a system safety and reliability tool for complex dynamic system such as nuclear reactors. Since 1960, great efforts have been made in solving fault trees to obtain reliability information about complex systems. Following the lead of the aerospace industry, the nuclear power industry discovered the virtues and benefits of fault tree analysis, and began using the tool in the design and development of nuclear power plants. Many key individuals in nuclear power industry contributed to advancing fault tree theory and fault tree software codes. In fact, the nuclear power industry may have contributed more to the development of fault tree analysis than any other single



user group. Many new evaluation algorithms were developed, along with software using these algorithms [47]. Today fault tree analysis is by far the most commonly used technique of risk and reliability studies. Fault tree analysis has particularly been used with success to analysis system in nuclear power station.

The fundamental concept in fault tree analysis is the translation of the failure behavior of a physical system into a visual model and structured logic diagram (fault tree), in which certain specified causes lead to one specified TOP event of interest. The diagram segment provides a visual model that very easily portrays system relationships and root cause fault paths. The logic segment of the model provides a mechanism for qualitative and quantitative evaluation. Fault tree analysis is based on reliability theory, Boolean algebra and probability theory [17, 38]. A very simple set of rules and symbols provides the mechanism for analyzing very complex systems, and complex relationships between hardware, software and humans.

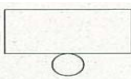


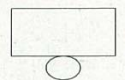








In assessing the condition of power transformer by using fault tree analysis, the first step is to model the system and failures sequences with a fault tree. Using minimal cut sets method, we can make qualitative evaluation of the model. This analysis will document the cause and effect relationship between failures at various subsystem levels, and identify the most important failures and weakness points in the systems. These characteristic helps to provide an appropriate maintenance to extend life service and increase the reliability of power transformers.

The purpose of this chapter is to analysis reliability of power transformer by using qualitative fault tree. The first step is to model the system and constructing a fault tree of power transformer based on its function and structure of main components. Then a top event was defined and the other events in the fault tree were identified stepwise by a deductive method. Top event in this study is 'the power transformer fails to convert low voltage of electricity to high voltage electricity'. Failure of the top event is made up of the failure of the five main apparatus (defined as the sub-top events). Then qualitative fault-tree analysis consists of determining the minimal cut sets and qualitative importance.

### 3.3 Symbology in Fault Tree

A typical fault tree is composed of a number of symbols which are described in table 3.1

Table 3.1 Fault tree Symbols

<b>a. PRIMARY EVENTS SYMBOLS</b>	
	BASIC EVENT- A basic event initiating fault requiring no further development
	UNDEVELOPMENT EVENT- AN event which is not further development either because it is of insufficient consequence or because information is unavailable
	HOUSE EVENT- An event which is normally expected to occur
	CONDITIONING EVENT- Specific conditions or restriction that apply to any logic gate (used primary with PRIORITY AND and INHIBIT gates)
<b>b. GATES SYMBOLS</b>	
	AND- Output fault occurs if all of the input faults occur
	OR- Output fault occurs if atleast one of the input faults occur
	COMBINATION-Output fault occurs if n of the input faults occur
	EXCLUSIVE OR- Ouput fault occurs if exactly one of the input faults occur
	PRIORITY AND- Output fault occurs if all of the input faults occur in a specific sequence ( the sequence is represented by a conditioning event drawn to the right of the gate)
	INHIBIT- output fault occurs if the (single) input fault occurs in the presence of enabling condition ( The enabling condition is represented by a CONDITION EVENT drawn to the right of the gate)
<b>c. TRANSFER SYMBOLS</b>	
	TRANSFER IN- Indicates that the tree $G_i$ is developed further at the occurrence of the corresponding TRANSFER OUT (e.g., on another page)
	TRANSFER OUT- Indicates that this portion of the tree $G_j$ must be attached at the corresponding TRANSFER IN

### **3.4 Power Transformer Description**

#### **3.4.1 Current Indonesia Electricity and Power Generation**

The power utility business in Indonesia is conducted only by the state-owned electricity utility, PLN (*Perusahaan Listrik Negara*) [1]. As the peak load is around 17 GW, it is obvious that 30% reserve margin as planned by PLN cannot be met which leaves the system in a vulnerable condition. The large difference between the total installed capacity and the rated capacity also suggests that these systems are backed up by some old renovated power plants. The PLN has decided this expansion, according to the Electricity Supply Action Plan 2006-2015 for the period 2006-2010, the targets on the transmission line development are interconnection within Sumatra in 2009, interconnection between Jawa-Bali and Sumatra in 2010 via submarine cable, and interconnection within Kalimantan (South, Central, East Kalimantan) in 2008 .

According to the Indonesia National Electricity Sector Master plan 2006-2026, the vision of the electricity sector is to electrify the entire residential sector, rural areas and to meet industrial demand in a sufficient, transparent, efficient, reliable, safe and environmentally friendly approach, to support national economic growth and the well-being of the Indonesian people [49]. In order to meet this vision, the missions are: to generate large-scale electricity for urban and systems/regions with high load capacity; to prioritize small-scale electricity generation for rural and remote areas using locally available renewable energy; to protect energy security and sustainable environmental functions; and to use local manpower, resources and services as much as possible.

The expansion of the electricity supply in Indonesia has been considered to meet the increasing of electricity demand, especially in Sumatra. This area is the biggest consumer of electricity outside of Java-Bali system and growth rapidly. Therefore PLN has a master plan to develop a new power plant and its infrastructure [5].

### **3.4.2 Power Transformer GI Simangkuk**

Asahan I hydro electric power plant is a new power supply for Sumatra interconnection. This plant produces 2 x 90 MW electricity. Simangkuk Switchyard is built by PLN to connect Asahan I with Sumatra interconnection system. This site has been operating since January 2011. Simangkuk is operated by computer system control (substation automation system, SAS) and equipped with 4 power transformers 275 kV [3]. Protection systems of Simangkuk switchyard is equipped with software and computer system. This equipment is digital high voltage protection equipment by PC and can be used as main protection and backup protection for 220 kV and higher voltage grade power transmission lines. This software also protects transformers from any abnormal conditions [6].

A 275 kV power transformer in GI Simangkuk in Indonesia serves as an example in this dissertation. The 275 kV power transformers converts low voltage electricity which is produced by hydro power plant Asahan I, to high voltage electricity, and then transfer it to high voltage transmission system of Sumatera interconnection system[4]. In this study we assume the type of power transformer is power auto-transformer with the specification as follows [7, 39, 48] :

- a. Type 250 MVA, 275 kV, Three windings
- b. Cooling system oil immersed, forced oil (FA)-forced air (FA) cooling system equipped with fans, oil pumps and radiators.
- c. Power transformer equipped with standard accessories which consist of bushing, conservator, Buchholz relay, pressure relief device, sudden pressure relay, dehydrating breather, oil gauge and thermometer.
- d. Power transformer equipped with optional accessories, On-Load Tap Changer.

The integrity of a power transformer depends upon the condition of its major components and a weakness in any component can lead ultimately to a major breakdown in the operating of the transformer has a major influence on the ageing of the insulation and the life time of the unit.

The main components are the bushing, winding, core, OLTC, tank, cooling system and accessories whilst the key parameters are strength and rigidity of the winding, the moisture content and ageing of the insulation, the quality and moisture content of the oil and the operating temperature. Transformer loading is mainly restricted by its winding hot spot temperature. High hot spot temperature causes acceleration of transformer insulation ageing and may lead to premature failure of power transformer. [40, 41]

Insulation electrical breakdown is the main reason of faults in the power transformer. It is well-known that insulation deterioration is a function of temperature, moisture and oxygen content. Today, with modern oil preservation systems, the moisture and oxygen content can be minimized, leaving the temperature as the controlling parameter.

### **3.5 Fault Tree Construction**

Fault tree analysis is very powerful as a systematic methodology for identifying root causes, plus it also provides a visual communication model that most individuals can readily understand and follow with a little knowledge of the tool, the system design or the accident situation. This visual model displays the logical relationship in the chain of events leading to a failure in power transformer system.

One of the strengths of fault tree is that it provides an approach to organize failure speculation in a structured graphical manner. Every parts, faults, cuts, conditions and relationships are displayed in standardize graphical notation that is very easy to understand and follow. The model can be easily modified as more data and information becomes available or any redundant equipment added to the system.

Fault tree construction is generally a complicated and time consuming task. Computer aided synthesis has attracted considerable attention and several methodologies have been proposed. In this research, the Relx computer software is employed to develop and calculate fault tree. General methodology for construction: David Haasl devised a structure that establishes rules to determine the type of gate to use and inputs to the gate [53].

A fault tree is constructed for each main apparatus (sub systems) of power transformer. The failure properties of these sub systems are lumped together by the fault tree to indicate the failure of the power transformer. The complete structure of fault tree of power transformer system is given in appendix 1. The first step in constructing FTA is to determine the single top event to be assessed and by deductive methods to expanding to sub system until no more gates to be expanded. The final fault tree for the failure of the power transformer has a top event which cause is given by the failure of any five of sub systems (bushing OR winding OR core OR OLTC OR tank). Every sub system expanded base on its hardware and its function of every single components in the whole systems. The expanding of fault tree is stopped when no more components needed to develop nor more sufficient data exists [38]. After the fault tree are completed all sub system are transferred into minimal cut sets.

### **3.5.1 Top event of fault tree**

The top event of fault tree is “power transformer fails to convert low voltage to very high voltage electricity”. This top event related to the main function of power transformers. Any failure of the main apparatus (five subsystems) will lead to the top event, as shown in Figure 3.1.

### **3.5.2 Five sub systems of the fault tree**

The lower levels of fault tree were identified stepwise by a deductive method. The sub system of tree contains with five main apparatus of power transformer (bushing, winding, core, OLTC, tank) as follows winding failure inducing electricity, core failure to be path of magnetic flux, bushing failure to transfer electricity, tank rupture or leaks and OLTC failure. On the tree, all events are basically correlated with a Boolean logic operator AND gate and OR gate for static fault tree and for dynamic fault tree correlated by Priority AND gate. In this study, causes for a particular events is searched based on a survey, literature or expert knowledge, and regarded as the event on the next hierarchical level. Then a cause for

next event is searched, and this procedure is repeated until the basic events in the lowest hierarchical level of the tree are identified.

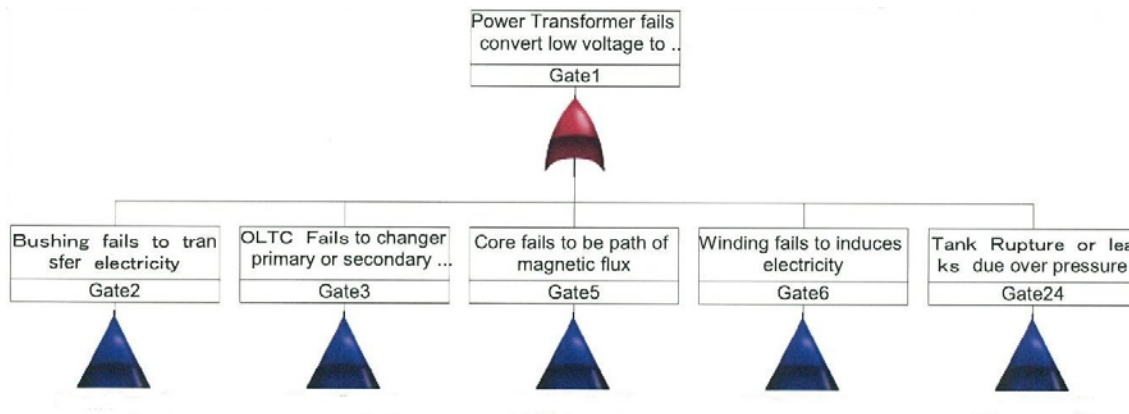


Figure 3.1 Top event of power transformer fault tree

### 3.5.3 Bushing fails to transfer electricity

Bushing systems are devices designed to pass winding to the outside of the transformer. The shape and dimensions of the bushings used on power transfers vary according to the operating voltage and current.

Figure 3.2 illustrates the fault tree of bushing. In the viewpoint of this function alone, the sub-top event is the bushing fails to transfer electricity from power plant to transformer (low voltage bushing) and from transformer to line transmission (high voltage bushing). Bushing main components are conductive part (copper or aluminium) and insulating part (porcelain).

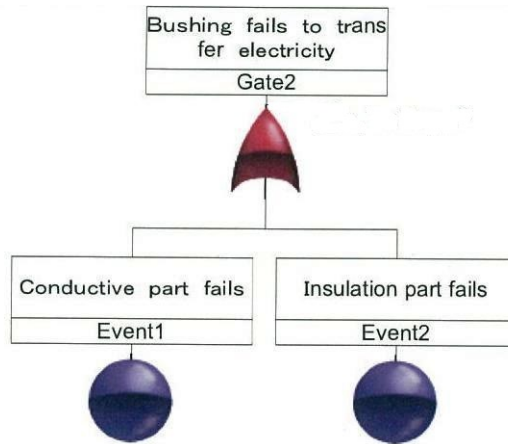


Figure 3.2 Fault tree of bushing

### 3.5.4 On Load Tap Changer (OLTC) fails to switch the connection

The OLTC is used to change the tapping connection of the transformer winding while the transformer is energized. The tap changer can be designed as a single unit for single and three phase applications with common neutral point. Depending on the three phase rating, it might require three separate units, each having its own insulated phases. Tap changer can be located either inside the transformer main tank or outside its own compartment.

Switching from one position to another has to be performed through an impedance to avoid a short circuit between two steps of the regulating winding. The transition impedance can be either a resistor or a reactor.

The On Load Tap Changer consists of tap selector switch, control devices and drive mechanism. Any failure on this part will lead the On Load Tap Changer failure. See, figure 3.3)



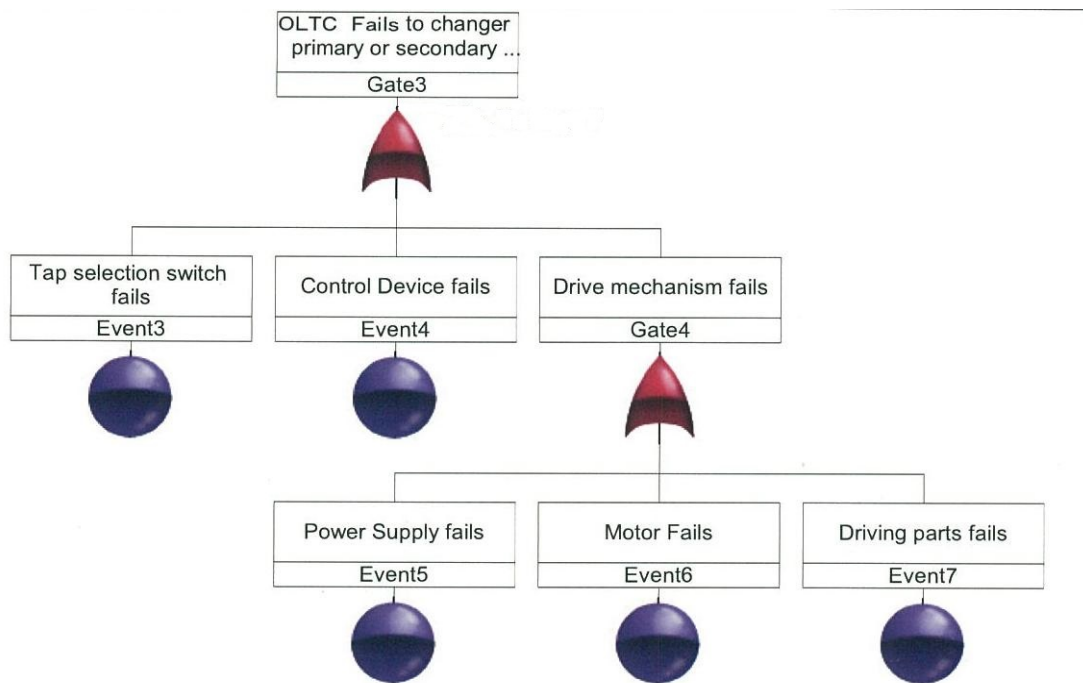


Figure 3.3 Fault tree of OLTC

### 3.5.5 Core fails to be path of magnetic flux

The purpose of a transformer core is to provide a low-reluctance path for the magnetic flux linking primary and secondary windings. The availability and reliability depend on quality of the core. Generally the core is composed of steel and designed with specific characteristic to obtain an excellent magnetic properties. Figure 3.4 shows the fault tree of the core system.

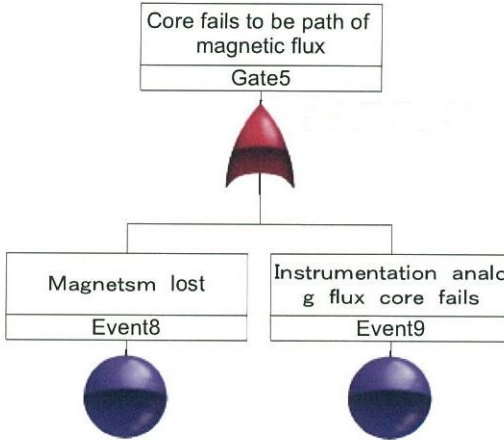


Figure 3.4 Fault tree of Core

### 3.5.6 Winding fails to induces electricity

The windings mainly comprise of copper, paper and pressboard. The paper and pressboard are impregnated with oil. Winding is made from several wires are wrapped together as a coil element with successive layers of insulation paper. The number of layers depending upon the working voltage gives sufficient dielectric strength to the layer insulation.

The resistive and other losses generate in transformer windings heat. This heat must be transferred into and taken away by the transformer oil. The winding copper retains its mechanical strength up to several hundred degrees Celsius. Transformer oil does not significantly degrade below about 140°C, but paper insulation deteriorates with greatly increasing severity if its temperature rises above about 90°C. The cooling oil must flow, therefore, ensure that the insulation temperature is kept below this figure as far as possible.

The standard reference temperature for the load losses of power transformers shall be 85°C. The maximum temperature at which no degradation of paper insulation occurs, is about 80°C. The standard reference temperature for the no-load losses of power transformers shall be 20°C [42]. Insulation life would greatly exceed transformer design life and, since ambient temperatures and applied loads vary, a maximum temperature of

80°C would mean that on many occasions the insulation would be much cooler than this. Thus, apart from premature failure due to a fault, the critical factor in determining the life expectancy of a transformer is the working temperature of the insulation or, more precisely, the temperature of the hottest part of the insulation or *hotspot*. Operation at only 10°C above the transformer rating will cut transformer life by 50 % [8].

A thermometer that measures top-liquid temperature shall be mounted on the side of the tank. This thermometer is connected to the contact relay which provides the ability to turn on cooling stage, alarm, or trip. The alarm contacts shall be adjustable over a minimum range of 40°C to 120°C [11].

Cooling systems are designed to protect the main component from any fault which causes overheating during operation. There are many type of cooling system according to class of the transformer. In this research, we focus on the cooling system of the Very Large Power Transformer Forced Oil-Forced Air class.

#### **3.5.6.1 Oil Pumps.**

The transformer is cooled by pumping oil or forced oil through a radiator normally attached to the outside of the tank. Main component of the pump is flow indicator, pump isolation valves and pump motor. It is important to ensure that motors are turning in the proper direction, if the motor reversed, the current will be much less than the nameplate full-load-current. Flow indicator should be in good condition and showing the oil flows. Pump isolation valves should work properly to ensure oil is circulating properly.

#### **3.5.6.2 Fans and Radiators.**

Air forced by fans over the cooling surface (radiators). Inspection of cooling fans and radiators is important to ensure their cleanliness as well as proper rotation of fans. Fans are much more efficient if the blades are clean and rotating in cool air. Normally, fans blow cool air through radiators, they should not be pulling air through. It is important to make sure that fans are not in reversed. This means the blades are rotating in cool air through the radiators which are more efficient.

### **3.5.6.3 Free Breathing Conservator.**

This design adds an expansion tank above the transformer so that the main tank may be completely filled with oil. Oil expansion and air exchange with the atmosphere breathing occurs away from the oil in the transformer. This design reduces oxygen and moisture contamination because only a small portion of oil is exchanged between the main tank and conservator.

An oil/air interface still exists in the conservator, exposing the oil to air. Eventually, oil in the conservator is exchanged with oil in the main tank, and oxygen and other contaminants gain access to the insulation.

### **3.5.6.4 Top Oil Thermometer**

These are typically sealed spiral-bourdon-tube dial indicators with liquid-filled bulb sensors. The bulb is normally inside a thermometer well, which penetrates the tank wall into the oil near the top of the tank. As oil temperature increases in the bulb, liquid expands according to the spiral tube. The tube is attached to a pointer that indicates temperature. This pointer also have electrical contacts with trigger alarms and start cooling fans as it shows temperature increase. Extra pointer, normally red, indicates maximum temperature since the last time the indicator was reset. This red pointer rises with the main pointer but will not decrease unless manual reset; thus, it always indicates the highest temperature reached since being set.

### **3.5.6.5 Winding Temperature Thermometer.**

These devices are supposed to indicate hottest spot in the winding based on the manufacturer heat run test. At best, this device is only accurate at top name plat rated load and then only if it is not out of calibration [5]. They are not what their name implies and can be misleading. They are only winding hottest-spot simulators and not very accurate. There is no temperature sensor imbedded in the winding temperature which should not be relied on for accuracy. They can be used to turn on additional cooling or activate alarms as

the top oil thermometers do. This device works the same as the top oil thermometer, except that the bulb is in a separate thermometer well near the top of the tank.

#### **3.5.6.6 Oil Level Indicator.**

These are floats operated with the float mechanism magnetically coupled through the tank wall with the dial indicator. As level increases, the float rotates a magnet inside the tank. Outside the tank, another magnet follows (rotates), which moves the pointer. The centre of dial is normally marked with a temperature 25 degree Celsius. High and low also mark to follow level changes as the oil expands and contracts with temperature changes. The pointer should be at a reasonable level corresponding to the top oil temperature. Oil level indicator may also be electrical switches for alarms and possibly tripping off the transformer on falling tank level.

#### **3.5.7 Tank rupture due to overpressure.**

The transformer active part is housed inside the enclosure, commonly known as transformer tank, which is also used to be house of oil. Transformer tank is constructed from steel, some parts can be stainless.

Tanks may develop oil leaks, especially at connection. Small leaks may also develop in headers or individual pipes. Any leaks in tanks system will lead to the failure of the whole system.

##### **3.5.7.1 Sudden Pressure Relay**

Sudden pressure relay is a device designed to respond the sudden increase in gas pressure in a power transformer which would be caused by internal arc. The relay is designed to detect a sudden pressure increase caused by arching. It is set to operate before the pressure relief device. Internal arching in an oil-filled power transformer can instantly vaporize surrounding oil, generated gas-pressure cause catastrophic failure, rupture tank spread flaming oil over a wide area.

The relay consists of three parts a pressure sensing bellows, a micro switch and a pressure equalizing orifice, all enclosed in a sealed case and mounted on the outside of the transformer at the gas space. The control circuit should de-energize the transformer and provide an alarm. The relay will ignore normal pressure changes such as oil-pump surges, temperature changes, etc.

#### **3.5.7.2 Pressure Relief Device**

These devices are the transformer last line defence against excessive internal pressure. In case of fault or short circuit, the resultant arc instantly vaporizes surrounding oil, causing a rapid build up of gaseous pressure. If the pressure relief device does not operate properly and pressure is not sufficiently relieved within a few milliseconds, a catastrophic tank rupture can result, spreading flaming oil over a wide area.

The pressure relief devices are spring-loaded valves that automatically reclose following a pressure release. The springs are held in compression by the cover and pressed on a disc which seals an opening. The pressure in the tank exceeds operating pressure, the disk moves upward to relieve the pressure. As pressure decreases, the springs reclose the valve. After the operation, this device leaves a brightly coloured rod (bright yellow for oil, blue for silicon) expose approximately 2 inches above the top. This rod is easily seen upon inspection, although it is not always visible from floor level. The rod may be reset by pressing on the top until it is gain recessed into the device.

#### **3.5.7.3 Buchholz Relay**

Buchholz relay is designed to detect faults as well to minimize the propagation of any damage which occurs within oil-filled transformers supplied with oil conservator. The relay is therefore particularly effective in case of ; short-circuited core laminations, broken-down core bolt insulation, bad contacts, overheating of some part of the winding, short-circuits between phases and earth faults puncture of bushing insulators inside the tank. Furthermore the relay can prevent the development of conditions leading to a fault in the

transformer, such as the falling of the oil owing to leaks, or the ingress of air as the result of defects in the oil circulating system.

The Buchholz relay is usually installed between the main tank and the oil expansion tank (conservator) of the power transformer. The relay housing is made from cast iron, having two flanged openings and two sight glasses showing a graduated scale of gas volume. There are two inside floats, usually the upper float is forced to move downward (this also in the case of oil leakage). On the other hand, in the case an excessive gassing causes an oil circulation through the relay, the lower float reacts, even before the gas reaches the relay. In both cases, the floats make contact when they are displaced [52].

### **3.6 Qualitative Analysis of Power Transformer Fault Tree**

In this study, the qualitative analysis of the fault tree resulted in minimal cut sets (MCS's) and qualitative structure importance. Qualitative analysis is used to identify what combinations of events cause the top event occur. It can be performed prior to the entry of failure or repair data in the properties for the events in the fault tree. Based on gate logic, qualitative analysis determines the minimal cut sets for the top event.

#### **3.6.1 Minimal Cut Sets**

The cut sets imply any sets of basic events that cause the top event, and the minimal cut sets imply only the least-needed cut sets events. The minimal cut sets thus highlight the most significant failure combinations and show where design changes can eliminate or reduce undesirable combinations. Minimal cut sets also support fault tree validation which specific minimal cut sets can be checked to determine whether they indeed cause the top event. Minimal cut sets can furthermore be reviewed for dependencies and susceptibilities to CCF (common cause failure) potentials. The minimal cut sets thus provide valuable, qualitative information as well as quantitative information [4].

Table 3.2 List of Minimal cut sets (MCS's) of power transformer

No	Sub systems	Minimal Cut Sets	Number of Single Basic event of MCS's	Number of doubleBasic event of MCS's
1	Bushing	Event 1, event 2	2	0
2	Winding	event10,event11,event12,event13,event14,event15,event16,event17,event18,event19,event20,event21,event22,event23,event24,event25,event24,event25,event26,event27,event28,event29,event30,event31,event32,event33,event34,event35,event36,event37,event38,event39,event40,event41,event42,event43,event44,event45,event46,event47,event48	38	0
3	Core	event8,event9	2	0
4	OLTC	event3, event 4, event 5,event6,event7	5	0
5	Tank	(event58,event67), (event59,event68),(event59,event67),(event59,event66), (event59,event65),(event59,event64),(event59,event63), (event58,event68),(event60,event62),(event62,event61), (event58,event66),(event59,event62),(event60,event63), (event60,event64),(event60,event65),(event60,event66), (event67,event61),(event60,event68),(event58,event65), (event63,event61),(event64,event61),(event65,event61), (event66,event61),(event49,event52),(event60,event67), (event51,event55),(event49,event53),(event61,event68), (event49,event55),(event49,event56),(event50,event52), (event50,event53),(event50,event54),(event50,event55), (event50,event56),(event51,event52),(event49,event54), (event51,event54),(event58,event64),(event51,event56),	0	50



Table 3.3 Qualitative importance of sub system

No	Sub systems	Number of Single Basic event of MCS`s	Number of doubleBasic event of MCS`s	Occurrence Probabilities
1	Winding	38	0	0.038
2	OLTC	5	0	0.005
3	Bushing	2	0	0.002
4	Core	2	0	0.002
5	Tank	0	50	0.00005

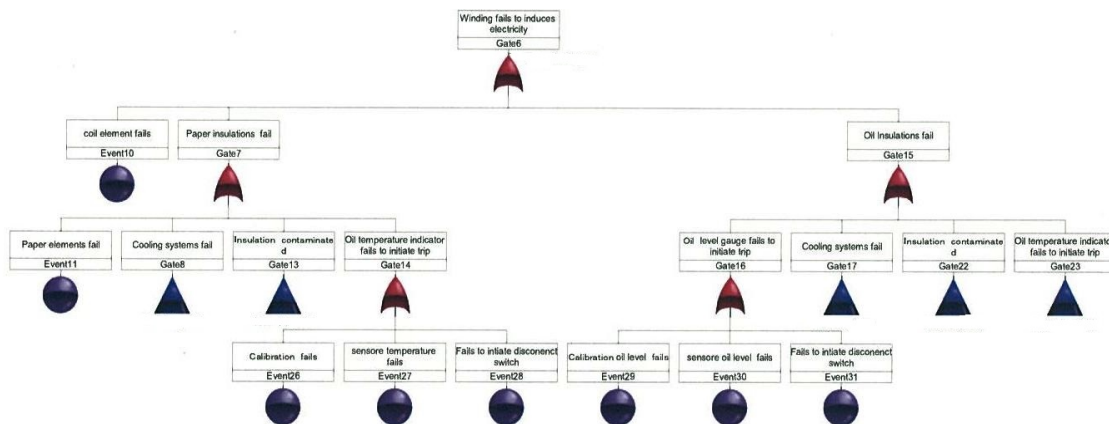


Figure 3.5 Fault tree of windings.

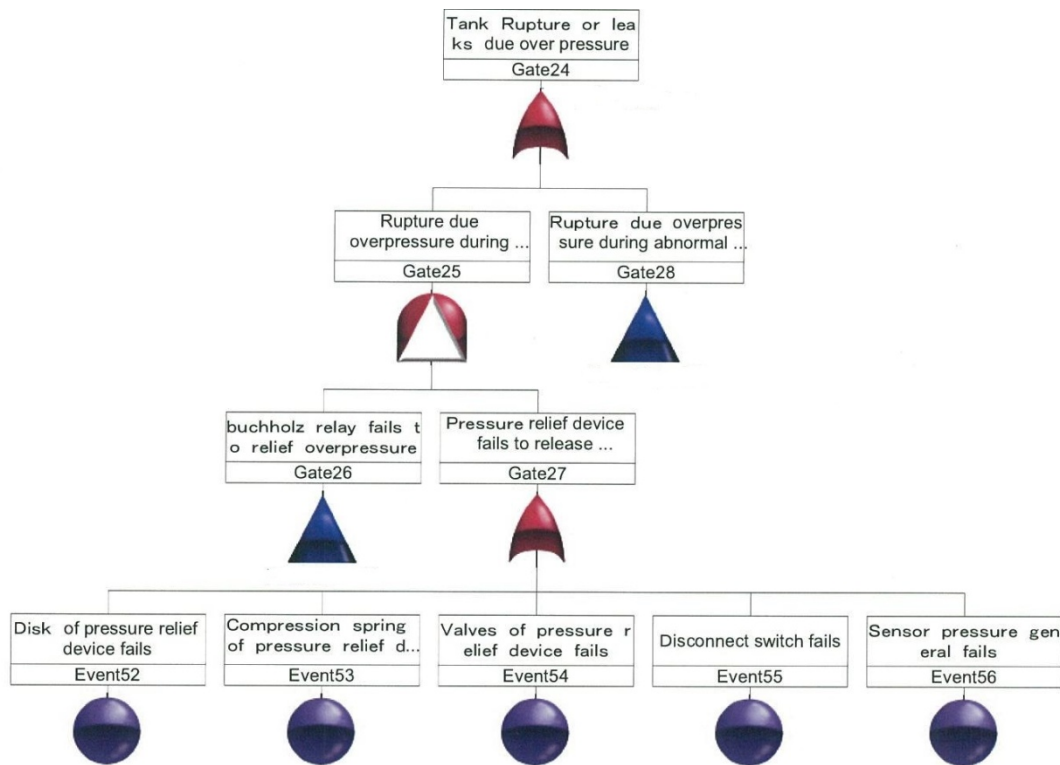


Figure 3.6 Fault tree of tank

While it is possible to determine minimal cut sets visually when the fault tree is very small, this is very difficult when the fault tree is large. Thus, computer algorithms have been developed to automate cut set generation. There are several approach for obtaining minimal cut sets of the fault tree such as MISCUP, MOCUS and ZBDD. MISCUP stands for minimal cut set upward, it uses a bottom-up approach, finding cut sets for gates at the lowest level of the fault, then obtains minimal cut sets of the upper level gates by substituting minimal cut sets of lower level gates, using Boolean reduction rules when applicable [64]. ZBDD stands for Zero-suppressed Binary Decision Diagram. It is based on advanced data structures knows as binary decision diagrams (BDDs) [65].

MOCUS stands for method of obtaining cut sets. Proposed by Fussell and Vesely in 1972, it uses a top-down approach based on the observation that OR gates increase the

number of cut sets and AND gates enlarge the size of the cut sets. This method is used in this research ( Relex software) as well as other fault tree analysis tools [66-70] .

An minimal cut set gives a necessary condition for power transformer failure to occur. The minimal cut sets are given in table 3.1. It shows 48 minimal cut sets with one basic event and 50 minimal cut sets with two basic events. The power transformer system has many possibility of the occurrence of basic events failure which lead to the occurrence of the top event. Any occurrence of the minimal cut sets will directly correspond to the occurrence of the top event, the power transformer failure to convert low voltage of electricity to high voltage of electricity.

### **3.6.2 Qualitative Structure Importance**

In qualitative structure importance evaluation, the more basic events are included in a minimal cut set, the less the minimal cut sets contributes to the occurrence of the top event and vice versa. Qualitative importance gives a qualitative ranking on each sub system with regard to its contribution to system failure.

Table 3.2 shows the qualitative importance of power transformer. Assuming that basic event occurrence probabilities are the same and less than 0.001, the rankings of qualitative importance of fault tree is obtained as : winding sub system (38 single basic events with occurrence probabilities 0.038), OLTC sub system (5 single basic events with occurrence probabilities 0.005), bushing ( 2 single basic events with occurrence probabilities 0.002), core (2 single basic events with occurrence probabilities 0.002) and the lower qualitative importance is tank ( 50 double basic events with occurrence probabilities 0.00005). The winding sub-system contain 39 single-basic-event minimal cut sets with occurrence probabilities 0.038, this indicates that winding sub-system is the highest ranking in qualitative structure importance which means the winding sub-system is the weakness point in the power transformer system. The tank sub-system contain 50 double-basic-events of minimal cut sets with occurrence probabilities 0.00005, this indicates that tank sub-system is the strongest point of power transformer system.

Assuming every component is independent, the ranking of qualitative component importance is given in table 3.2. The more single-basic-event of minimal cut sets are included in a component, the more significant contribution to the occurrence of the top event.

Based on this result, it is important to focusing attention on winding sub-system that the most contributed to the unreliability of the power transformer system. The consistency of this result with the general weakness of the power transformer [1,40,41].

### **3.7 Summary and Conclusion**

In this chapter, reliability of power transformer is assessed using qualitative fault tree analysis. The qualitative analysis of the fault tree resulted in minimal cut sets and qualitative importance.

An important feature of the fault tree analysis is very powerful as a systematic methodology for identifying root causes, it also provides a visual communication model that most individuals can readily understand and follow with a little knowledge of the tool, the system design or the accident situation. In this chapter, the visual model displays the logical progression in the chain of events leading to failure in power transformer. The 275 kV power transformer in GI Simangkuk, Indonesia serves as example in this chapter.

The qualitative results help in focusing attention on main apparatus of power transformer that contributed to the unreliability of the system. Through qualitative fault tree analysis of power transformer can be found that the strongest and the weakest point are tank sub-system and winding sub-system, respectively [71].

Future work, by the quantitative fault tree analysis, represents a quantitative analysis of the power transformer.

Table 3.3 The ranking of qualitative component importance

No	Sub systems	Component name	Number of Single Basic event of MCS`s	Number of doubleBasic event of MCS`s	Occurrence Probabilities
1	Winding	Oil temperature indicator	6	0	0.006
		Oil level gauge	6	0	0.006
		Winding temperature indicator	6	0	0.006
		Radiators	6	0	0.006
		Fans	6	0	0.006
		Pumps	2	0	0.002
		Conservator Breather	2	0	0.002
		Automatic control	2	0	0.002
		Coil Element	1	0	0.001
		Paper Element	1	0	0.001
2	OLTC	Drive mechanism	3	0	0.003
		Tap Selection switch	1	0	0.001
		Control Device	1	0	0.001
3	Bushing	Conductive part	1	0	0.001
		Insulation part	1	0	0.001
4	Core	Magnetism	1	0	0.001
		Instrument analog flux	1	0	0.001
5	Tank	Nomal Operation (Buchholzrelay and Pressure relief device)	0	25	0.000025
		Abnormal oepration (sudden pressure relay and pressure relief device)	0	25	0.000025

## **Chapter 4**

# **Quantitative Fault Tree Analysis of Power Transformer**

### **4.1 Introduction**

Power transformer is one of the main equipments in power systems used to convert low voltage to very high voltage electricity intended to upgrade efficiency in power electricity transmission. When a failure occurs in a power transformer, the whole system will be failed and the electricity could not be delivered to customer. Each utility has to assure their reliability in order to maintain electrical power system stability by assessing power transformer condition [37]. In recently years, there are many methods have been proposed to assess the reliability of power transformer, several monitoring techniques are used and under investigations [2].

The purpose of this chapter is to assess the reliability of power transformer using quantitative fault tree. The first step in the quantitative evaluation of a fault tree is to find the structural representation of the top event in terms of the basic events. In previous work, we were proposed the qualitative fault tree analysis of power transformer as a base for the quantitative analysis [56].

If the rate of occurrence and fault duration for all basic events are known and the statistical dependency of each basic event is known (or assumed), then the statistical expectation or probability of top event can be determined [57]. The purpose of quantitative analysis of a fault tree usually is to determine the probability of the top event (system failure).

## **4.2 Fault Tree Method**

### **4.2.1 Fault Tree Analysis**

The fault tree analysis is a tool to identify and assess the combinations of the undesired events in the context of system operation and environment that can lead to undesired state of the system. It is recognized worldwide as an important tool for safety and reliability in system design, development and operation. The undesired state of the system is represented by a top event [17,38]. Fault tree analysis can be used to identify the system weakness and evaluate possible upgrades. Furthermore, fault tree analysis can be used to diagnose causes and give potential corrective measures for an observed system failure. This method has been used and refined over the ensuing years, is attractive because it does not require extensive theoretical work and it is a practical tool that any engineer can learn to use easily [17]. A fault tree is classified as static or dynamic based on the types of gates used. If only static gates such as AND, OR and k-out-of-n are used in the fault tree, it is called a static fault tree. If a fault tree contains sequence-dependent gates as well as static gates, the tree is called a dynamic fault tree [58].

The basic idea of the proposed transformer condition assessment analysis is quantitative fault tree analysis to obtain the probability of component failure leading to a power transformer failure. A fault tree analysis is a logic diagram that shows potential events affecting system performance and the relationship among potential events [74]. Fault tree analysis is a tool with which protection engineers can easily compare the reliability of proposed protection of transformers.

To quantify the probability of the top event or sub top event of the fault tree a probability for each basic event (failure probability of every components) in the fault tree must be provided. These basic component probabilities are then propagated upward to the top event using Boolean relationships for the fault tree. Alternatively, the minimal cut sets can be generated from the fault tree and then used to quantify the top event or sub top event. In this study, the fault tree of power transformer system can be divided into independent modules[55], and the modules solved separately, then the separate results can be combined to achieve a complete fault tree analysis.

#### 4.2.2 Quantitative Fault Tree Analysis

In assessing the condition of power transformer by using fault tree analysis, the first step is modeling the system and failures sequences with a fault tree [3]. A quantitative analysis is used to identify the likelihood of occurrence of the top event in the fault tree and those of each minimal cut set. Quantitative results include the top event unavailability, unreliability or failure rate. The top event parameters are defines as follows :

unavailability :  $A(t)$  the probability that the system failure mode exists at time  $t$ .

Unreliability :  $R(t)$  the probability that the system failure occurs at least once from time  $t$  to time  $t$ .

Failure rate : the rate at which the system failure mode occurs.

All of these quantities can be used to judge the acceptability of the system performance [54].

To perform quantitative fault tree analysis, firstly a failure rate must be obtained and entered in the calculation properties for each lowest-level event in the fault tree. When quantitative fault tree are calculated, the unreliability of the system can be computed. These measures, rather than reliability, are computed because fault tree's are organized around failures rather than successes.

When fault tree calculation are performed, first determines whether the fault tree is static or dynamic. Any fault tree that includes a dynamic gate is considered a dynamic fault tree. Dynamic fault tree are broken down into corresponding modules, and each module is individually analyzed as a static or dynamic entity [76]. To generat exact calculated results, the static entities are computed using standard combinatorial techniques, which consider conditional event and gate probabilities in the same manner as BDD's. The dynamic entities are transformed into equivalent Markov models. The results for these various entities are then brought together for generalized fault tree analysis to produce exact calculations.



#### 4.2.2.1 Quantification of the fault tree static gates

To calculate the probability of occurrence of top event in fault tree, it is necessary to understand the relation among the top, intermediate, and basic events. To quantify the probability of the top event of the power transformer fault tree, a probability for each basic event in the fault tree must be provided. These basic event probabilities are then propagate upward to the top event using the Boolean relationship for the fault tree. Commonly used Boolean operators are, namely, AND and OR gates [17,37,38]:

Alternatively, the minimal cut set can be generated from the fault tree and then used to quantify the top event. The minimal cut set generation approach is used by most software because of the additional, important information provided by the minimal cut sets.

Since the top event is expressed as the union of the minimal cut sets, the probability of the top event can be approximated as the sum of the individual minimal cut set probabilities, provided these probabilities are small. Since the minimal cut set is an intersection of basic event's, the probability of a minimal cut set is simply the product of the individual basic event probabilities. Thus, the probability of the top event is expressible as the sum of the products of individual basic event probabilities. This expression is called the sum of products approximation.

In term of symbols the sum of products expression is given as :

$$P(TE) = \sum P(MCS_i)$$

$$P(MCS_i) = P(BE_1) P(BE_2).....P(BE_k) \quad (4.3)$$

Where :

$P ( )$  = the probability of the enclosed event

TE = s the top event

$MCS_i$  = a particular minimal cut set

$BE_j$  = basic event j

k = the number of basic events in a minimal cut set

#### 4.2.2.2 Dynamic gates

A dynamic gate considers the temporal order of the occurrence of input events. This means that the order of the occurrence of inputs events is important to determining the output. In this research the type of dynamics gate is priority AND gate ( P-AND). The P-AND gate is used to indicate that the output occurs if and only if all input events occur in a particular order. These two special gates (P-AND ) are part of the dynamic fault tree (DFT) methodology that has been developed specifically for the analysis of computer-based system [60].

A dynamic fault tree model can not be easily evaluated using traditional fault tree analysis techniques, such as those that are based on cut sets or other Boolean logic techniques. Since the dynamic fault tree gates must capture the order in which events occur, not simply their probability of occurrence, a Markov model used for solution. The equivalent Markov model can be generated from the dynamic fault tree and then solved using ordinary integrals equations or some approximations [75].

The dynamic entities are transformed into equivalent Markov models. The algorithm for converting a dynamic fault tree to an equivalent Markov model is conceptually simple [60]. Starting with the initial state ( all components as good as new), a set of target states and associated transitions are generated by considering the effect of failing each active component, one at time. Each time a new state is generated, it is checked against the fault tree to see if it is an operational or failed state. Each operational target state is added to Markov chain and is further expanded [61].

The use of a Markov model to solve dynamic fault trees offers a significant advantage. The Markov model permits failure effects that depend on the order in which components fail to be captured in the analysis. However , the solution of a Markov model is much more time and memory consuming than the solution of a standard fault tree model [17]. The size of a Markov model ( in terms of the number of states and transition) grows exponentially with the number of basic components in the fault tree of power transformer system. For a system with many components, the solution of a system using Markov model may be infeasible, even if the model is truncated.

In the fault tree of power transformer system dynamic part of the system is shown in figure 4.1 and figure 4.2. This independent dynamic module can be solved as a Markov model. When the Markov model is solved, its probability of failure is incorporated into the rest of the fault tree, which is now static due it has no dynamic gates and can be solved via conventional fault tree analysis techniques.

This modularized approach to fault tree analysis has several important advantages. First, it allows for the use of the more efficient static fault tree analysis methodology where it applies, and the Markov approach is used only where necessary. Further, even if every module is dynamic, separate Markov models can be developed for each module, which can result in an enormous saving time.

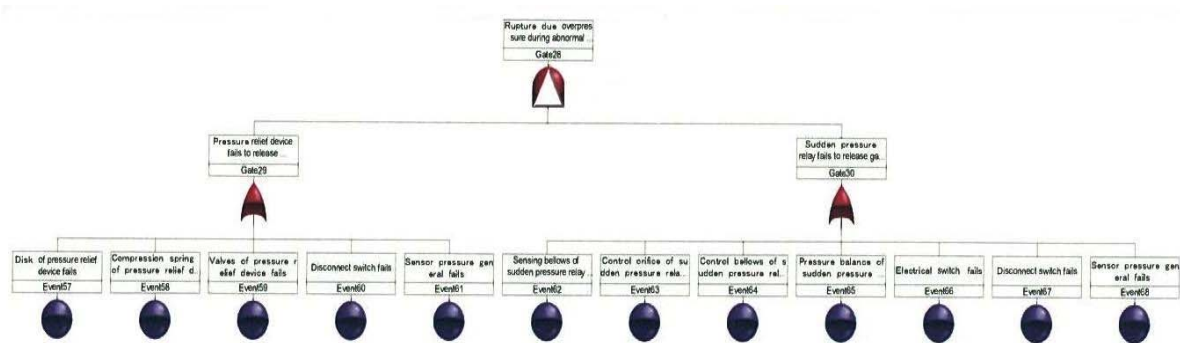


Figure 4.1 Dynamic fault tree of tank gate 28

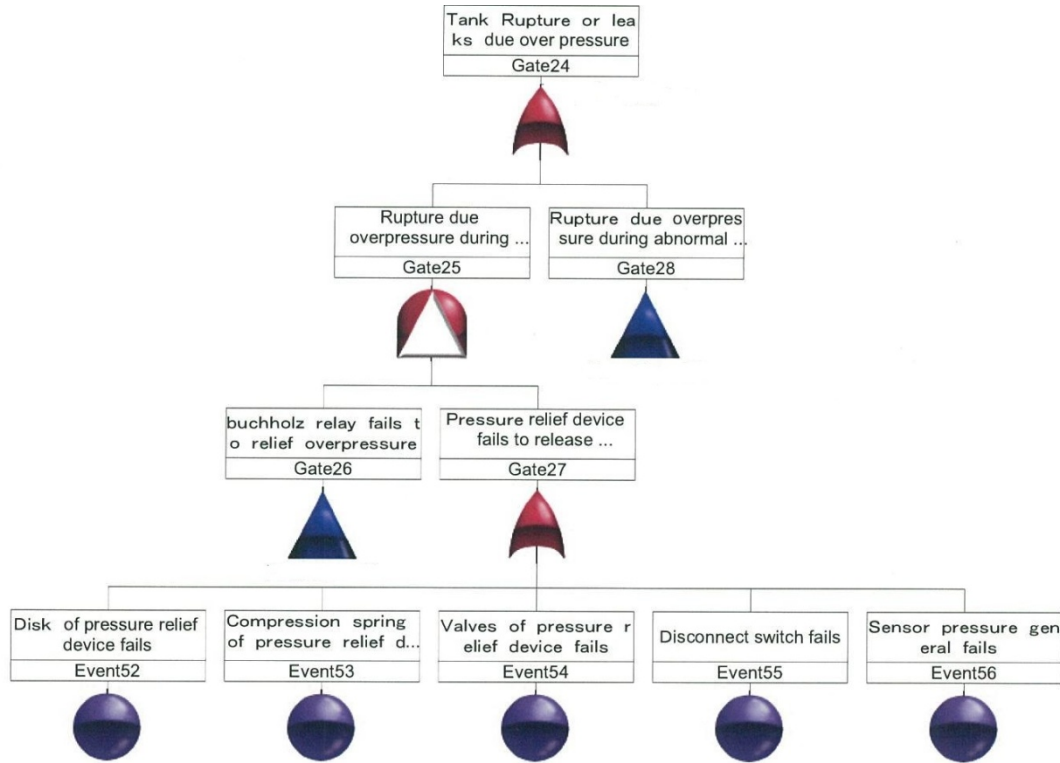


Figure 4.2 Dynamic fault tree of tank gate 25

#### 4.2.3 Failure probabilities

Failure rates data of International Atomic Energy Agency (IAEA) data are considered as failure rates for some basic components are given in table 1 [59]. These failure rates are a good estimate for the real failure rates of basic components of power transformer system.

The Unreliability,  $F(t)$ , is defined as the probability that the component or system experiences the first failure or has failed one or more times during the time interval zero to time  $t$ , given that it was operating or repaired as good as new at time zero.

$$R(t) + F(t) = 1 \text{ or Unreliability } F(t) = 1 - R(t) \quad (4.4)$$

$$R(t) = e^{-\lambda t}, \text{ where } \lambda = \text{the failure probability per unit time and } t = \text{time } t$$

A Relx software is employed to developed model of power transformer system and calculate their associated unreliability. The calculations are based on independent device failure rates.

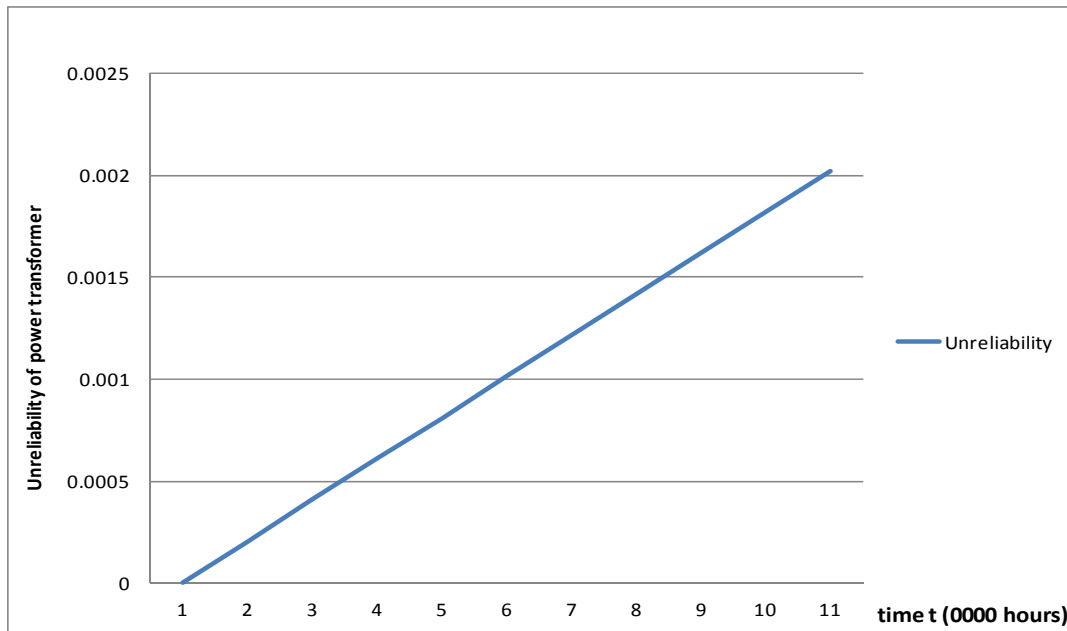


Fig.4.3 The probability occurrence of the top event during operation at time t

### 4.3. Result and Analysis

#### 4.3.1 Power Ttransformer Model

A 275 kV power transformer in GI Simangkuk in Indonesia serves as an example in this paper. The power transformer's is employed to convert low voltage electricity which is produced by hydro power plant Asahan I, to be high voltage electricity, then transfer it to high voltage transmission system of Sumatera interconnection system[7]. In this study we assume the type of power transformer is power auto-transformer with the specification as follows : Type 250 MVA, 275 kV, windings system, cooling system oil immersed, forced oil-forced air cooling system equipped with fans, oil pumps and radiators, bushing, Buchholz relay, pressure relief device, sudden pressure relay, and On-Load Tap Changer.

Table 4.1 Failure rates basic components of power transformer

No	Sub system	Basic component	Failures rate/hr
1	Bushings	Conductive part	1.0000E-06
		insulation part	3.7000E-06
2	OLTC	Tap Selection switch	4.0000E-07
		Control device	1.0000E-04
		Power supply	3.0000E-04
		Motor	3.0000E-05
		Driving mechanism	3.2000E-06
3	Tank	Disk of Pressure relief device	2.8000E-05
		compression spring of Pressure relief device	2.8000E-05
		valves of pressure relief device	3.5000E-05
		Lower Float of Buchholz relay	1.0000E-06
		Upper Float of Buchholz relay	1.0000E-06
		Valves of Buchholz relay	1.3000E-05
		Sensing bellows of sudden pressure relay	8.7000E-06
		control orifice of sudden pressure relay	3.0000E-04
		Control bellows of sudden pressure relay	1.0000E-04
		Pressure balance of sudden pressure relay	1.0000E-04
		Electrical Switch of sudden pressure relay	1.0000E-04
		Disconnect switch	7.0000E-04
		heat exchanger	8.7000E-05
		Magnetism	1.0000E-06
		Instrumentation analog core flux	8.2000E-06
5	Winding	Coil element	1.0000E-06
		Paper elements	1.0000E-06
		Disconnect switch	7.0000E-04
		silica gel	3.0000E-05
		Sponge filter	3.0000E-05
		sensor flow general	4.0000E-06
		automatic control	1.0000E-04
		fans	3.5000E-06
		pumps	1.0000E-06
		Up valve of radiator	2.4000E-05
		bottom valve of radiator	2.4000E-05
		Fans dirty	6.0000E-06
		Power supply/diesel engine general	3.0000E-04
		Pump motor driven feed water	9.9000E-04
		blades	1.0000E-06
		Switch Temperature	5.3000E-06
		sensor level general	2.1000E-03
		sensor pressure general	8.7000E-06

In our previous work had performed fault tree model constructed of the power transformer to investigate the causes for the fault in power transformer operation given in [37]. The causes were deductively identified as the event causing every possible hazard by constructing a fault tree. The fault tree analysis was constructed in a hierarchical structure with a single top event . The top event in this study is the power transformer fails to convert low voltage of electricity to high voltage electricity. The fault tree model should be based on performing of quantitative fault tree analysis.

#### 4.3.2 Top Event Occurrence Possibilities

The probability of occurrence of the top event , i.e., failure of the power transformer is obtained by Relx software on the probability occurrence of top event and subsystem at time  $t=0$  until time  $t = 100000$  results given in Table 3.3. This result shows representation of future behavior of the system in terms failure and success of power transformer system. The top event represents the power transformer failure or unreliability. The five sub system (intermediate gates) representing power transformer failure are bushing fails to transfer electricity from power transformer to the distribution line and to source line, on load tap changer (OLTC) fails to changer primary or secondary windings, core fails to be path of magnetic flux, winding fails to induces electricity from primary winding to secondary winding, and tank rupture or leaks due overpressure during operation.

The intermediate gates connected to the top event through OR gates, this means that any occurrence of the intermediate gate will leading to the occurrence of the top event . Table 3.3 also shows the rankings of quantitative contribution to the occurrence of top event is obtained as : winding sub-system, OLTC sub, bushing sub-system, core sub-system, and the lowest contributor is tank sub-system. At time  $t = 100000$  hours the probability of the occurrence of the top event (power transformer failure) and intermediate events is given in figure 4.4.

Table 3.3 shows the probability occurrence and percentage contribution of failure probability every sub system and the occurrence of the top event at any time  $t$ . At any time during operation time of power transformer, we can obtained the probabilities occurrence

of every gates and top event. It means the behavior of the system can be predicted in order to improve reliability services and better maintenance. The winding sub-system is the most contribute to the occurrence of the top event in any time, this indicates that winding sub-system is the weakness point in the power transformer system. The bushing sub-system is the strongest point of power transformer system. Based on this result, it is important to focusing attention on winding sub system that the most contributed to the unreliability of the power transformer system. The consistency of this result with the general weakness of the power transformer [1, 40,41].

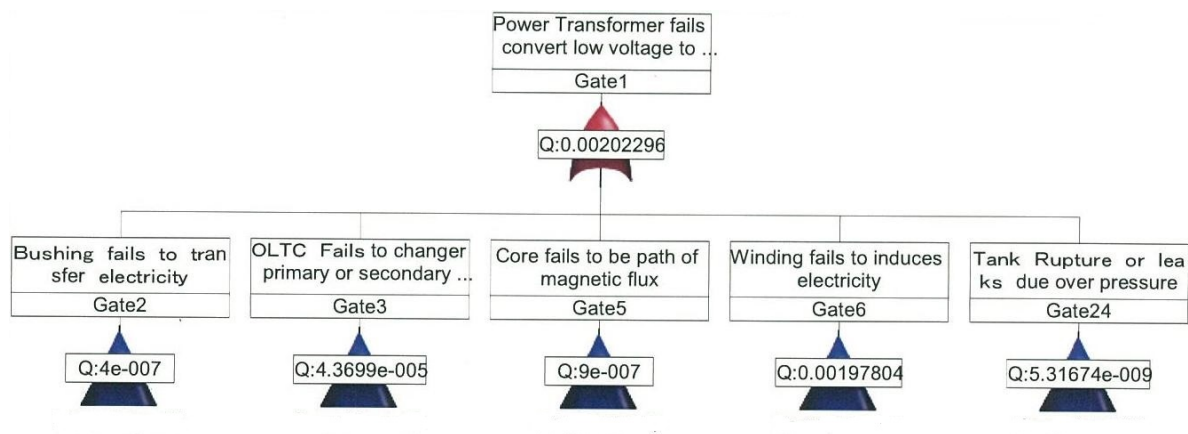


Fig 4.4 The probability of the top event and sub-system t time t = 100000 hours.

The possibility of the occurrence of the top event will be increased by the increasing operation time of the power transformer as given in figure 4.3.

#### 4.4 Summary and Conclusion

The quantitative fault tree analysis of power transformer of GI Simangluk in Indonesia is performed. The result of the quantitative fault tree analysis depends on the failure rate of every single-basic-events or components which connected to the gates through static and dynamic gates. The probability of occurrence of the top event (power transformer failure) and every gates are obtained by quantitative methods. Furthermore the winding sub-system and the bushing sub-system is the most and the less contributed to the occurrence of the



top event, respectively. This means that utmost care should be taken to prevent the occurrence of the winding sub-system failure.

Table 4.2 Failure probability and percentage contribution to the occurrence of top event

Time t (hours)	Sub System										Top Event	
	Winding		OLTC		Tank		Core		Bushing			
	Pr	%	Pr	%	Pr	%	Pr	%	Pr	%	Pr	%
0	0	0	0	0	0	0	0	0	0	0	0	0
10000	2.00E-04	97.777	4.40E-06	2.158	5.00E-11	0.059	9.00E-08	0.044	4.00E-08	0.0198	2.00E-04	100
20000	4.00E-04	97.777	8.70E-06	2.159	2.00E-10	0.118	1.80E-07	0.044	8.00E-08	0.0198	4.00E-04	100
30000	6.00E-04	97.777	1.30E-05	2.159	5.00E-10	0.177	2.70E-07	0.044	1.20E-07	0.0198	6.00E-04	100
40000	8.00E-04	97.777	1.70E-05	2.159	9.00E-10	0.236	3.60E-07	0.044	1.60E-07	0.0198	8.00E-04	100
50000	1.00E-03	97.776	2.20E-05	2.159	1.00E-09	0.295	4.50E-07	0.044	2.00E-07	0.0198	0.001	100
60000	0.001	97.776	2.60E-05	2.159	2.00E-09	0.354	5.40E-07	0.044	2.40E-07	0.0198	0.001	100
70000	0.001	97.776	3.10E-05	2.16	3.00E-09	0.414	6.30E-07	0.044	2.80E-07	0.0198	0.001	100
80000	0.002	97.776	3.50E-05	2.16	3.00E-09	0.473	7.20E-07	0.044	3.20E-07	0.0198	0.002	100
90000	0.002	97.776	3.90E-05	2.16	4.00E-09	0.532	8.10E-07	0.044	3.60E-07	0.0198	0.002	100
100000	0.002	97.775	4.40E-05	2.16	5.00E-09	0.591	9.00E-07	0.044	4.00E-07	0.0198	0.002	100
Ranking		1		2		3		4		5		

## **Chapter 5**

# **Components Importance Analysis of Fault Tree**

### **5.1 Introduction**

Component importance analysis is a key part of the system reliability quantification process which are most effective towards safety improvement. The importance measure is a useful guide during system development phase as to which component should receive more urgent attention in achieving system reliability growth.

To achieve high reliability for a complex system, it is necessary to identify the components and sub-systems that have the greatest effect on the system reliability. Such items can be identified using importance measures that rank the items quantitatively according to their contribution to system unreliability. These top importance measures establish the significance for all events in the fault tree in terms of their contributions to the top event probability. Both intermediate events (gate events) as well as basic events can be prioritized according to their importance. Top importance measures can also be calculated that give the sensitivity of the top event probability to an increase or decrease in the probability of any event in the fault tree.

What is often useful about the top event importance is that they generally show that relatively few events contribute to the top event probability. In many past FTAs, less than 20% of the basic events in the fault tree important contributors, contributing than 90% of the top event probability. Moreover, the importances of events in the fault tree generally cluster in groups that differ by orders of magnitude from one another. In these cases, the importances are so dramatically different that they are generally not dependent on the preciseness of the data used in the FTA. In addition to providing the significance of the contributors, the top importances can be used to allocated resources. These resources might include testing and maintenance resources, inspection resources, upgrade resources, and wide variety of other resources. By using the top importances, resources can be optimally

adjusted to minimize total resources expenditures with maintaining the top event probability.

In addition to allocating resources, the importances can be used to assign allowed downtimes and repair times, to focus diagnostics activities in identifying the causes of a top event, and to focus design activities and requirements in design applications.

Many importance measures have been presented, eq. B-Imp, product importance, criticality importance, risk achievement worth, and risk reduction worth. Such measures are usually defined and calculated at the component level (basic event level in a fault tree). In this research, three basic types of importance measurement will be calculated for the applications in power transformer. The most often used are Birnbaum importance measures, critically importance measures, and Fussel-Vessely importance measures [77,79].

Importance components of a power transformer system must be analyzed carefully to ensure system reliability and safety. Failure of more importance component can lead to higher cost associate with operation and maintenance of the system, priority should be given to components that are more important according to their safety and reliability importance [1].

This chapter presented the importance measures analysis of a power transformer system in GI Simangkuk switchyard in Indonesia by using Birnbaum importance measures, critically importance measures, and Fussel-Vessely importance measures. These importance measures are used to identify which functional element is most likely to cause a system failure. This can lead to the identification of the path to increase the overall system reliability by either procuring more reliable functional elements or adding redundancy. This method also present the rank of the component importance measures quantitatively according to their contribution to system unreliability and safety.

Firstly, the fault tree models are created and the reliability of fault tree are calculated. Secondly, cut set analyses are performed to determine functional elements most likely to fail in the fault tree. Thirdly, importance measures are calculated for each functional element. Lastly, identical basic components are grouped to provide the understanding of

which basic components had the most significant impact on the power transformer system reliability and safety.

## **5.2 Fault Tree Analysis of Power Transformer**

The FTA is a tool to identify and assess the combinations of the undesired events in the context of system operation and its environment that can lead to undesired state of the system. It provides a logical framework or understanding the ways that lead to system failure. The undesired state of the system is represented by a top event [2]. The scenarios are originated from basic events, and described by a series logical operator and intermediate events leading to the top event. A fault tree is classified as static or dynamic based on the types of gates used. If only static gates such as AND, OR and k-out-of-n are used in the fault tree, it is called a static fault tree. If a fault tree contains sequence-dependent gates as well as static gates, the tree is called a dynamic fault tree [3].

A 275 kV power transformer in GI Simangkuk in Indonesia serves as an example in this chapter. The power transformers is employed to convert low voltage electricity which is produced by hydro power plant Asahan I, to be high voltage electricity, then transfer it to high voltage transmission system of Sumatera interconnection system[37].

We present fault tree model of power transformer based on our previous work given in [73]. This fault tree represent a 275 kV power transformer system that is equipped with three windings, cooling system oil immersed, forced oil-forced air cooling system, oil pumps and radiators, bushing, conservator, Buchholz relay, pressure relief device, sudden pressure relay, dehydrating breather, oil gauge, thermometer, and on-load tap changer. The logical ways leading to the top event are shown in [73].

The quantitative analysis of fault tree analysis requires the aid of computerized methods for their evaluation. The algorithms for the quantified fault tree analysis are well explained in [17, 53-55,57-58,60]. The quantitative fault tree analysis of power transformer was performed for a time period of up to 100.000 hours for services mission scenarios. The probability of the top event computed with the fault tree analysis in [73] is 0.00202286 at time  $T = 100.000$  hours.

### 5.3 Computation of Importance Measures

Importance analysis is a part of the system quantification process which enables the analyst to rank the contribution that each component makes to system failure of power transformer and thus identify the weakest areas of the system. In this chapter, three importance measure analysis methods are employed to evaluate power transformer system.

For this study, the individual basic components importance measures were divided by the sum of all importance measures to determine which element represented the most significant contribution to the fault tree reliability. The importance measure reflects how much relative improvement may be available from improving performance of a specific basic component. Change in the failure rates of the functional component or adding redundancy to account for the high failure rate with the highest importance measure percent contribution will have the most significant effect on increasing power transformer system reliability.

#### 5.3.1 Birnbaum Importance Measure (BIM)

A Birnbaum importance measure is the rate of change in the top gate probability with respect to the change in the unavailability of a basic event. Therefore, the ranking of events obtained using the Birnbaum importance measures is helpful when selecting the event to improve when the actual efforts for improvement is the same for all events. The Birnbaum importance measure can be used to evaluate the effect of an improvement in component reliability on system reliability. The BIM for event A can be calculated as the difference in the probability of the top event given that event A did occur minus the probability of the top event given that event A did not occur ( $\sim A$ ). The BIM is defined as:

$$\text{BIM}(A) = P\{TE|A\} - P\{TE|\sim A\} \quad (5.1)$$

Where : - A indicates the event whose importance is being measured

-  $\sim A$  indicates that this event did not occur

- TE indicates the top event

Birnbaum importance measures play a crucial role in defining several other importance measures and calculating several performance measures such as system failure frequency.

The BIM has been investigated and used in reliability optimization problems since it was first proposed by Birnbaum [78].

### 5.3.2 Criticality Importance Measure (CIM)

The criticality importance measure of event A is the probability that component A is critical for the system. The top event will occur follow the occurrence of component A. While the Birnbaum importance measure considers only the conditional probability that event A is critical, the CIM also considers the overall probability of the top event occurrence due to event A. Alternatively, the criticality importance measure modifies the Birnbaum importance measure by adjusting for the relative probability of basic event A to reflect how likely the event is to occur and how feasible it is to improve the event. These modifications enable the criticality importance measure to focus on truly important basic events and make it possible to compare basic events between fault trees. The Criticality importance measure is defined as:

$$CIM(A) = BIM(A) * P\{A\} / P\{X\} = (P\{TE|A\} - P\{TE|\sim A\}) * P\{A\} / P\{TE\} \quad (5.2)$$

Where : - X is the the top event occurs

While the Birnbaum importance measure consider the maximum possible improvement in the system performance with respect to event A while changing the event probability from 1 to 0, the criticality importance measure indicates the actual possible improvement from the current situation. Therefore, it is appropriate to use the criticality importance measure to improve system performance.

### 5.3.3 Fussell-Vesely Importance Measure (FVIM)

In the cases where event A contributes to the top event but is not necessarily critical, the Fussell-Vesely importance measure can be used. For an event to contribute to the top event, at least one cut set containing event A should occur. The Fussell-Vesely importance measure is the ratio of the probability of occurrence of any cut set containing event A and the probability of the top event.

$$FVIM(EA) = \frac{Pr(U \text{ MCS } A)}{Pr(TE)} \quad (5.3)$$

FVIM are constructed using minimal cut sets. If the objective is to minimize the individual contributions of basic events, then Fussell-Vesely importance measure should be used to select the basic event to improve.

#### **5.4 Importance Measures calculation and results**

The fault tree of power transformer system with single top event obtains five sub-systems. The sub system are bushing winding, core, OLT and tank. The fault tree of power transformer contains 68 basic events with 97 number of cut sets. The qualitative and quantitative analysis have obtained from our previous work [71,73].

The importance measure BIM, CIM and Fussell-Vesely importance measure of the basic events are produced from a RELEX fault tree analysis software and corresponding rankings are given in table 5.1. The winding sub-system contains the higher ranking of importance basic events in power transformer system. These are event 26 and event 47 (oil temperature indicator error in calibration), event 27 and event 48 (sensor of temperature failure), event 29 (oil level indicator error calibration), event 30 (sensor oil level indicator failure). These method present the rank of the component importance measures quantitatively according to their contribution to system reliability and safety.

This result shows that only 14 basic event give 89 % contribution to the power transformer system reliability .

#### **5.5 Summary and Conclusions**

It is an important task to identify those components in a system, which have the greatest impact on system safety. This is carried out in practice by first choosing a suitable measure of component importance, calculating them for each component and then ranking the importance of components according to that measure. In this paper we presented the various result which can be used to compare the relative importance system component [72]. These result are helpful to practical engineers, because calculating the exact value of the component importance measures is very laborious in power transformer systems.

Table 5.1 Ranking of component importance measures

Ranking	EventID	Birnbaum %	Criticality %	FussellVesely %
1	Event26	100	10.37003	10.37003
1	Event27	100	10.37003	10.37003
1	Event47	100	10.37003	10.37003
1	Event48	100	10.37003	10.37003
1	Event29	100	10.37003	10.37003
1	Event30	100	10.37003	10.37003
2	Event23	100	4.888999754	4.888999754
2	Event33	100	4.888999754	4.888999754
3	Event15	100	3.456918637	3.456918637
3	Event28	100	3.456918637	3.456918637
3	Event46	100	3.456918637	3.456918637
3	Event42	100	3.456918637	3.456918637
3	Event31	100	3.456918637	3.456918637
4	Event5	100	1.48156619	1.48156619
4	Event19	100	1.48156619	1.48156619
4	Event22	100	1.48156619	1.48156619
4	Event34	100	1.48156619	1.48156619
4	Event32	100	1.48156619	1.48156619
5	Event4	100	0.493860335	0.493860335
5	Event12	100	0.493860335	0.493860335
5	Event43	100	0.493860335	0.493860335
6	Event6	100	0.148158619	0.148158619
6	Event20	100	0.148158619	0.148158619
6	Event24	100	0.148158619	0.148158619
6	Event25	100	0.148158619	0.148158619
6	Event44	100	0.148158619	0.148158619
6	Event45	100	0.148158619	0.148158619
6	Event35	100	0.148158619	0.148158619
6	Event16	100	0.118526931	0.118526931
6	Event17	100	0.118526931	0.118526931
6	Event37	100	0.118526931	0.118526931
6	Event38	100	0.118526931	0.118526931
7	Event9	100	0.039509009	0.039509009
8	Event18	100	0.029631759	0.029631759
8	Event39	100	0.029631759	0.029631759
9	Event13	100	0.024693134	0.024693134
9	Event14	100	0.024693134	0.024693134
9	Event21	100	0.024693134	0.024693134
9	Event40	100	0.024693134	0.024693134
9	Event41	100	0.024693134	0.024693134
9	Event36	100	0.024693134	0.024693134
10	Event3	100	0.019754508	0.019754508
11	Event2	100	0.014815882	0.014815882
11	Event7	100	0.014815882	0.014815882
12	Event1	100	0.004938628	0.004938628
12	Event8	100	0.004938628	0.004938628
12	Event10	100	0.004938628	0.004938628
12	Event11	100	0.004938628	0.004938628
13	Event60	0.013159695	0.00045492	0.00045492
14	Event67	0.007989754	0.000276199	0.000276199
14	Event63	0.007989754	0.000118373	0.000118373
14	Event64	0.007989754	3.94582E-05	3.94582E-05
14	Event65	0.007989754	3.94582E-05	3.94582E-05
14	Event66	0.007989754	3.94582E-05	3.94582E-05
15	Event59	0.013159695	2.27468E-05	2.27468E-05
15	Event57	0.013159695	1.81974E-05	1.81974E-05
15	Event58	0.013159695	1.81974E-05	1.81974E-05
15	Event61	0.013159695	5.19926E-06	5.19926E-06
16	Event55	0.00015	5.18537E-06	5.18537E-06
17	Event51	0.007989754	5.12959E-06	5.12959E-06
17	Event62	0.007989754	3.15667E-06	3.15667E-06
17	Event68	0.007989754	3.15667E-06	3.15667E-06
18	Event49	0.007989754	3.94584E-07	3.94584E-07
18	Event50	0.007989754	3.94584E-07	3.94584E-07
19	Event54	0.00015	2.59277E-07	2.59277E-07
19	Event52	0.00015	2.07422E-07	2.07422E-07
19	Event53	0.00015	2.07422E-07	2.07422E-07
19	Event56	0.00015	5.92635E-08	5.92635E-08



## Chapter 6

### Conclusions and Topics for Future Research.

#### 6.1 Conclusions

This thesis is devoted to application of fault tree analysis in a power transformer system. The dissertation was roughly divided into three parts.

**The first part**, consist chapter 2, considered the importance and brief explanation of assessment and monitoring of power transformer. we describes the need of assessment and maintenance of power transformers such as outages effect of failures, high cost of maintenance and replacement, increase of world demand, aging effect and use of old transformer, and computer protection system failure. In this chapter we also present power transformer design and construction as well as the power transformer failures and problems. We also describes the monitoring and diagnostic methods of transformers assessment which have been developed in recently years.

**The second part** is chapter 3, shows the process of developing and constructing the model of fault tree of power transformer system based on switchyard GI Simangkuk system in Indonesia. The causes were deductively identified as the event causing every possible hazard by constructing a fault tree. The fault tree was constructed in a hierarchical structure with a single top event. Furthermore in this chapter we conduct the qualitative fault tree analysis of power transformer. Fault tree analysis of the power transformer was performed to investigate the causes for the fault in power transformer operation. Qualitative analysis on the fault tree yielded minimal cut sets and qualitative importance. By qualitative analysis of the fault tree analysis, we found the weakness of power transformer system.

**The third part**, consists of chapter 4 and 5, considered the quantitative analysis of power transformer fault tree. In chapter four, we conducted quantitative fault tree in assessing the reliability of power transformer for a switchyard. The first step is determines whether the fault tree is static or dynamic. To generated exact calculated results, the static entities are computed using standard combinatorial techniques. The dynamic entities are transformed into equivalent Markov models. The results for these various entities are then brought together using techniques employed for generalized fault tree analysis to produce exact calculations. This result will help the decision maker to improve the reliability of power transformer system. Chapter five, we conduct importance measures analysis of power transformer system components. we presented an application and results of the importance measures analysis of a power transformer system of GI Simangkuk switchyard in Indonesia by using Birnbaum importance measures, critically importance measure, and Fussell-Vessely importance measures. These method present the rank of the component importance measures quantitatively according to their contribution to power transformer system reliability.

Finally as conclusion of this thesis presents the fault tree method is a simple method and easy to apply for the power transformer system and recommend to utilities as an alternative method in order to contribute for resolving the reliability problem assessment of power transformer to ensure the safety operation and distribution of GI Simangkuk switchyard in Sumatera Electricity Interconnection, Indonesia.

## **6.2 Topics for Future Research**

Based on our study in this research, we proposed several recommended topics for future researches as follows,

1. Failure rate of every single basic event in fault tree, is one of the most important data to conduct quantitative fault tree analysis. The accuracy of failure rate of basic components are the most vital in quantitative fault tree analysis dealing

with accuracy of reliability analysis of power transformer system. The existing failure rate data of basic component as well as the methods to obtain failure rate data in power transformer system are very limited. This research topic become more important to apply of quantitative fault tree analysis.

2. The fault detection and analysis for power transformer are the key measures to improve the reliability and safety operation of power transformer. Due to the complexity of the power transformer structure and variety in operation condition, the occurrence of the fault in power transformer is uncertain and random. The important topic in the future research is the environmental operation condition of power transformer combined with the fault tree analysis, it is able to analyze the fault of power transformer system efficiently and comprehensively.
3. More researches are needed for better understanding how the power transformer system works dealing with determine dynamic parts and static parts of the fault. The more better understanding and description of the dynamic and static parts of power transformer system will produce better reliability assessment.

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## **Published Papers**

Most parts of this thesis have been either published as journal or conference as list is given below.

### **Chapter 2**

- [37] Sihite, J.F, Kohda T., “Power Transformers Condition Assessment of GI Simangkuk Switchyard Sumatra Interconnection in Indonesia,” Journal of Advanced Materials Research, Vol.452- 453, pp.975-979. (2012)

### **Chapter 3**

- [71] Sihite, J.F, Kohda. T, “Qualitative Analysis of Power Transformer Reliability by Fault Tree”, in Proceeding of Probabilistic Safety Assessment and Management (PSAM) and European Safety and Reliability (ESREL) conference, Helsinki. (2012)

### **Chapter 4**

- [72] Sihite, J.F, Kohda. T, “Components Importance Analysis Fault Tree of Power

Transformer of GI Simangkuk Switchyard in Indonesia ,“ Journal of Advanced Materials Research, Vol.694- 697, pp.907-910. (2013)

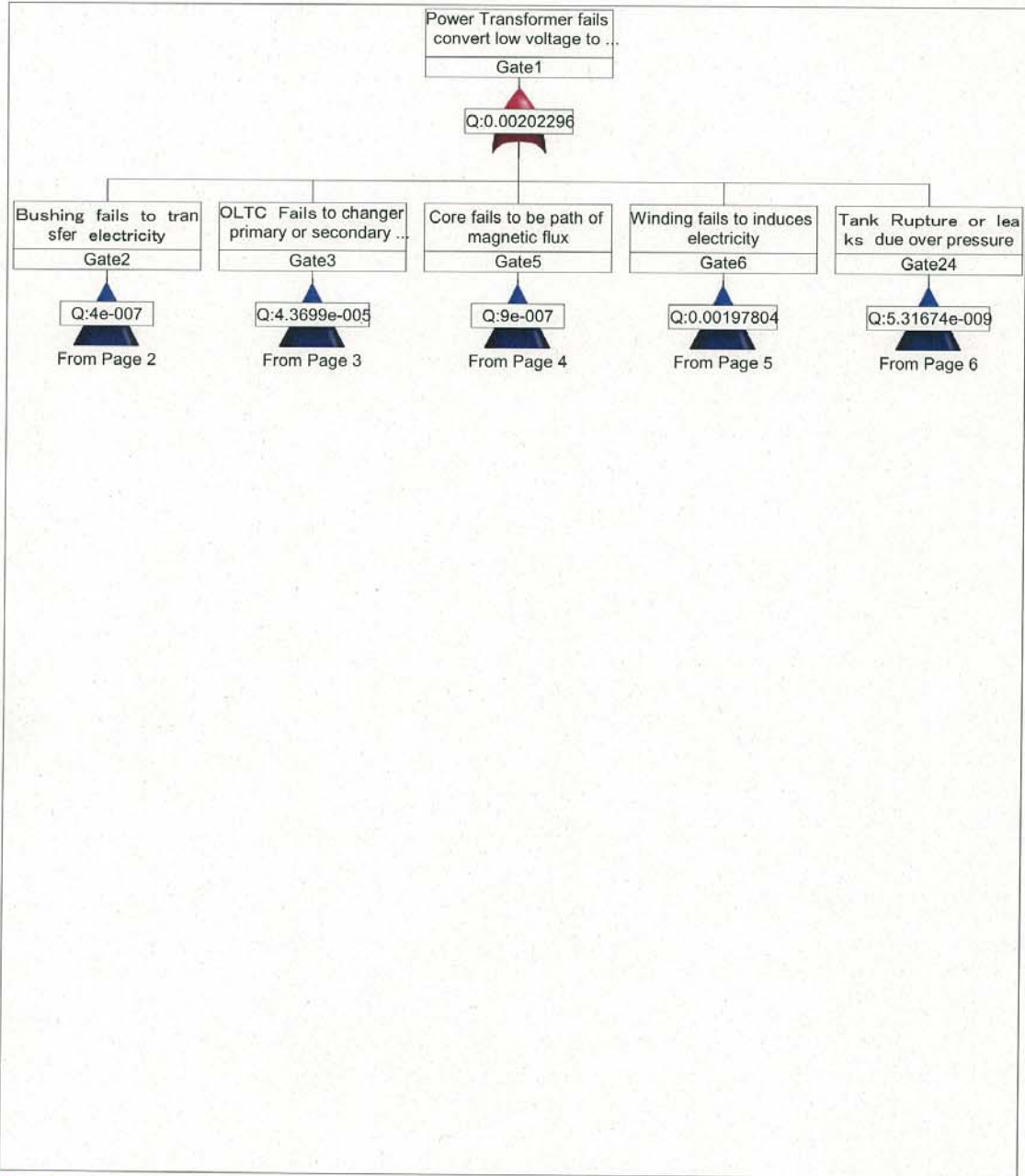
## **Chapter 5**

[73] Sihite, J.F, Kohda. T, “Assessing the Reliability of Power Transformer by Quantitative Fault Tree Analysis,” Journal of Advanced Materials Research, Vol. 694- 697, pp.901-906. (2013)

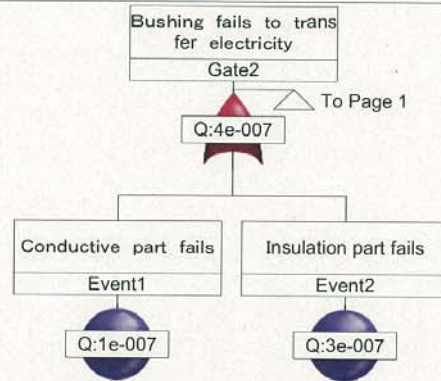
# **APPENDIX A**



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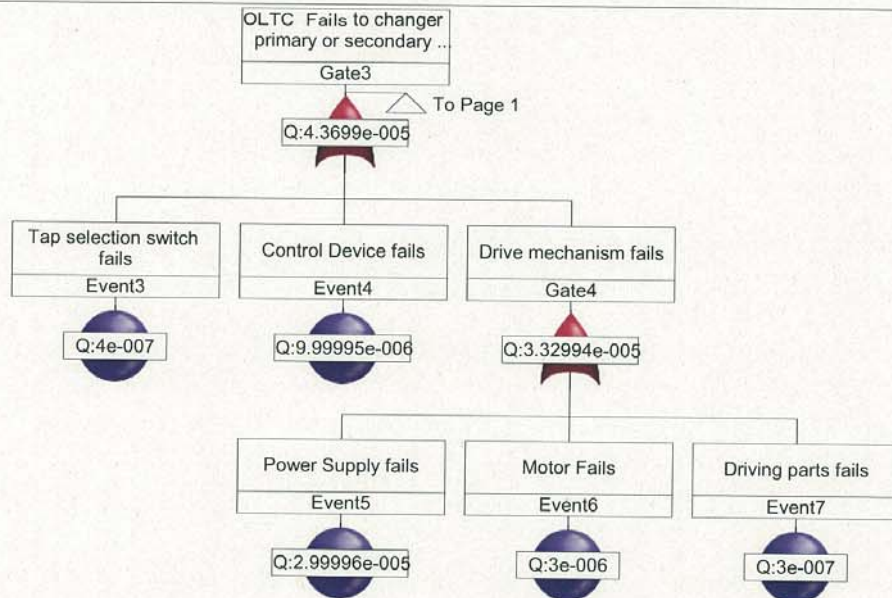


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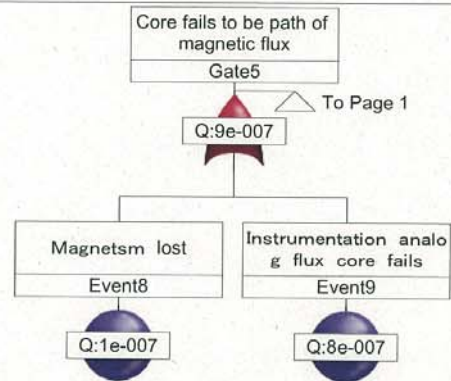




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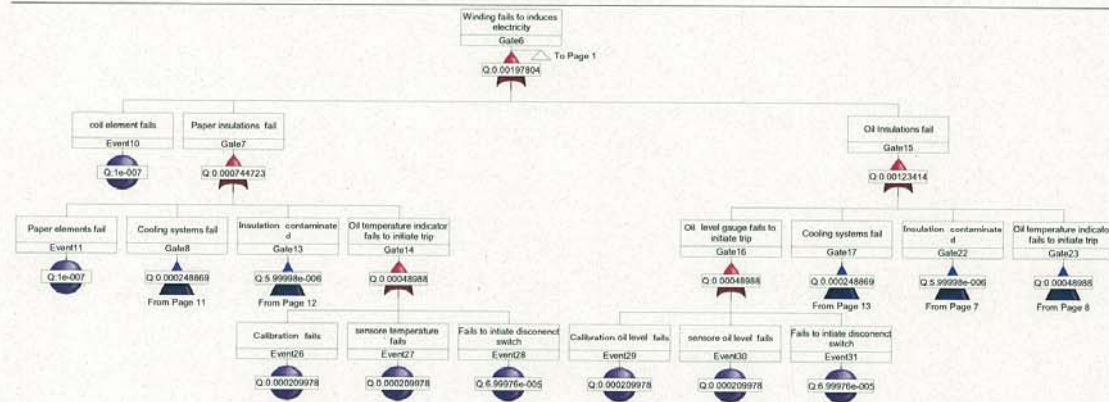
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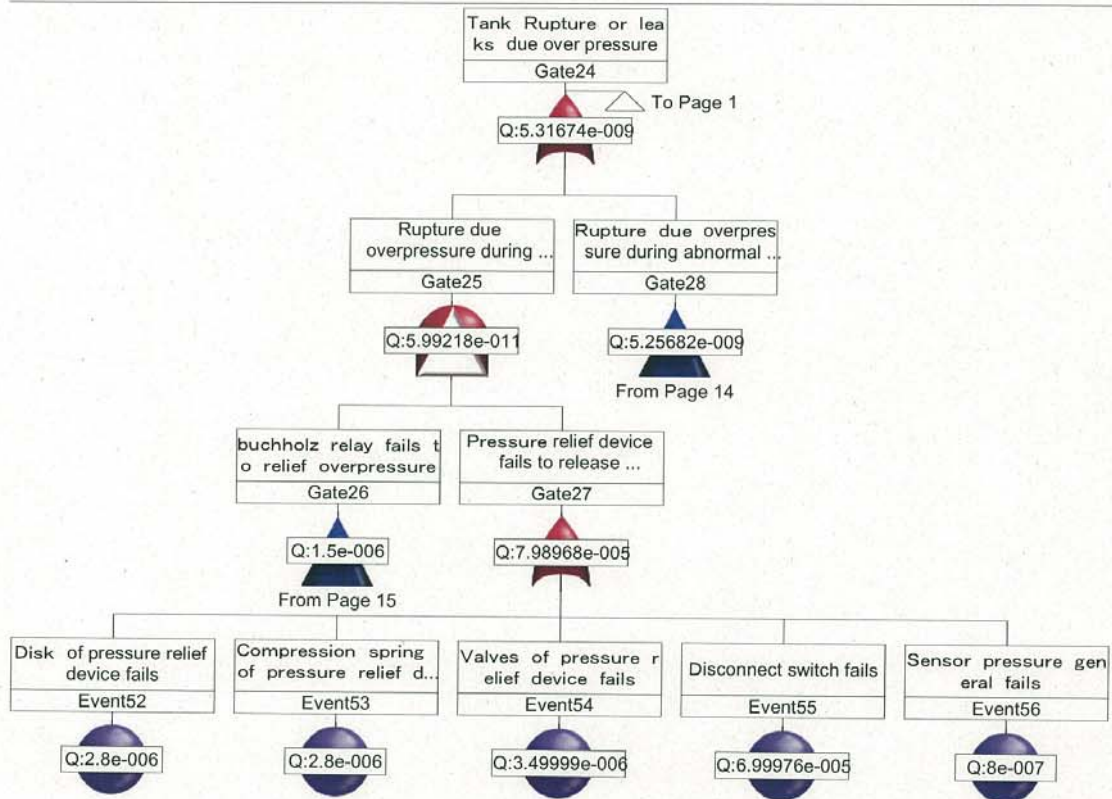


## Fault Tree Diagram

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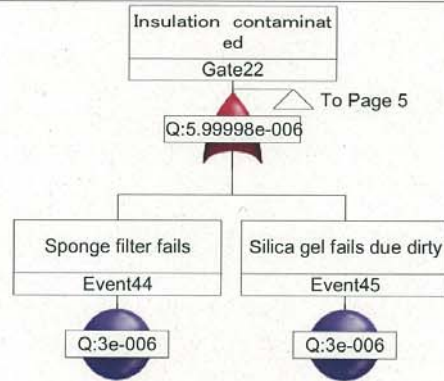


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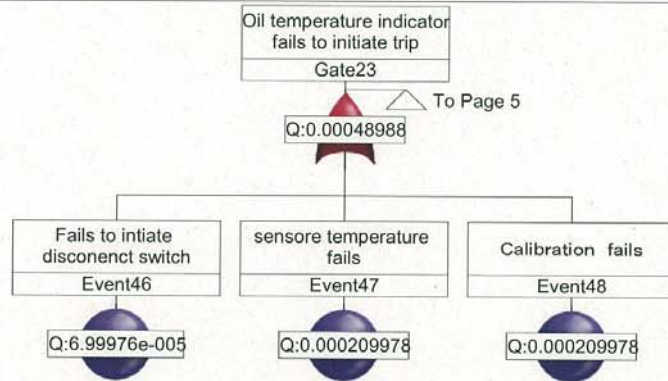




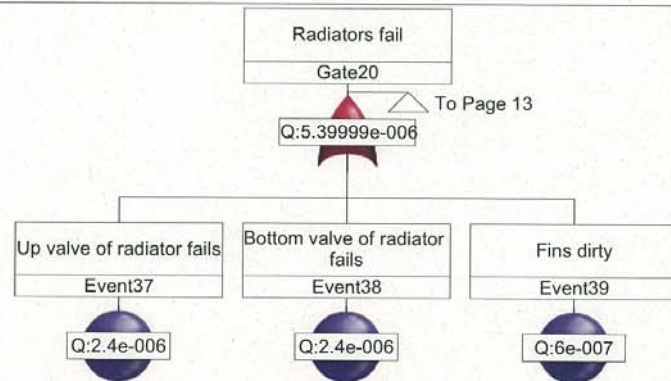
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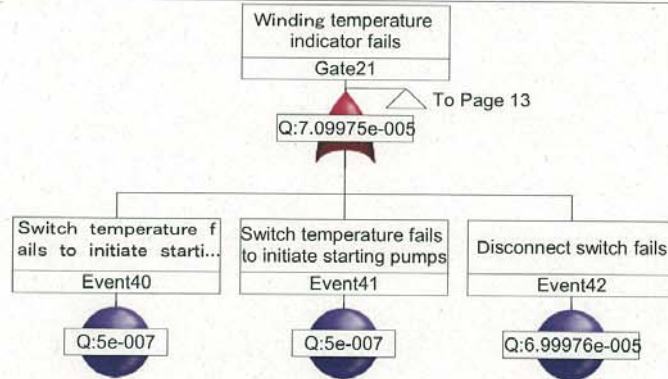
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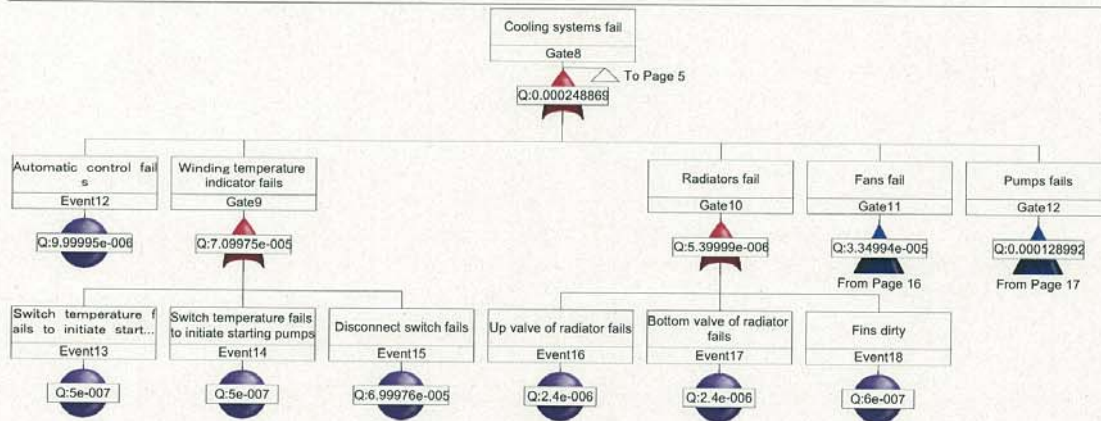


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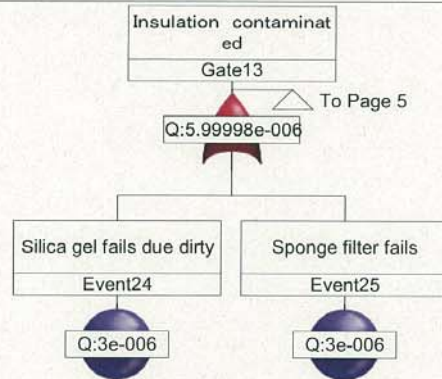




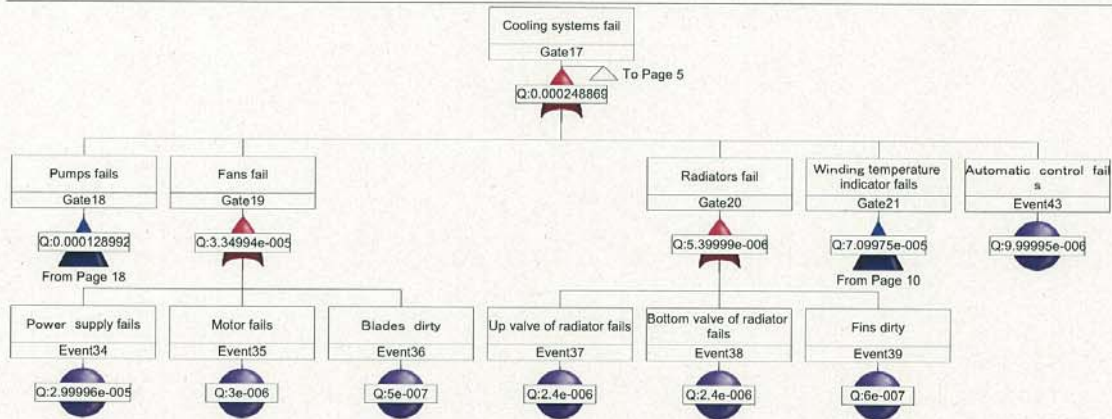
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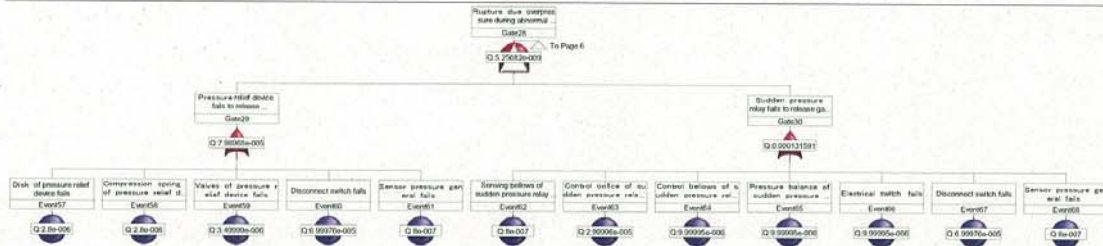
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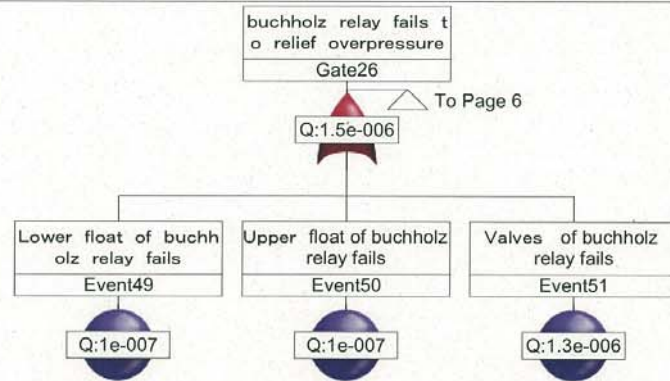


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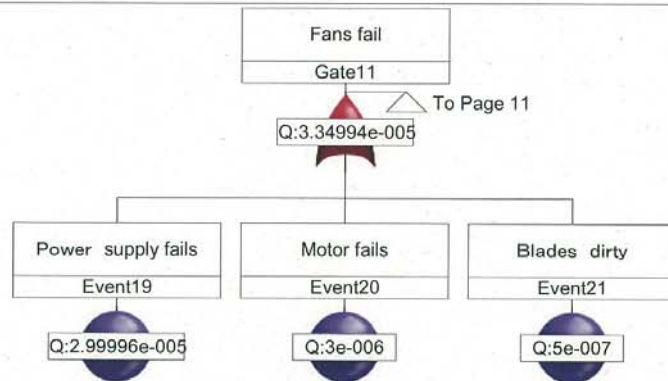




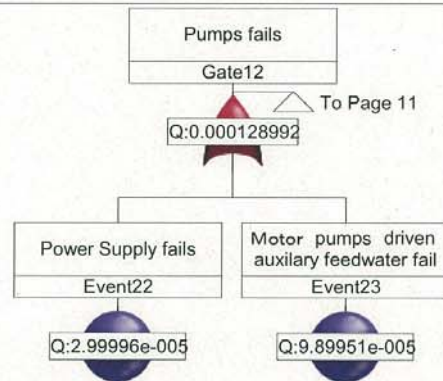
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